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Orienting Livestock Shelters to Optimize Natural Summer Ventilation

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Abstract. *Using the meteorological data of 10 Ontario weather stations, natural ventilation rates were computed for a typical gable roofed swine shelter, oriented at 6 different angles from the north. A nonparametric statistical procedure was used to identify that orientation giving the least period of ventilation under the required rate, throughout the summer, for temperature ranges above 20° C, 25° C, and 30° C.*

For all 10 stations, 1 or 2 building orientations gave slightly but significantly better ventilation rates than all other orientations. Ventilation was improved by further extending the period during which minimum summer rates were respected. Nevertheless, growers using properly oriented buildings and natural ventilation can expect low summer ventilation rates 12% to 27% of the time. These low ventilation conditions can persist over more than 24 consecutive hours in some locations. ***Keywords.** Natural ventilation, Orientation, Summer rates.*

Natural ventilation of livestock shelters requires the design of air inlets and outlets which maximize the occurrence of pressure differentials across these openings. The two principal natural phenomena which bring about these pressure differentials are: (1) prevailing winds causing zones of high and low static pressures around the building and (2) temperature differences between the air inside and outside the shelter causing buoyancy forces. Because these pressure differentials are created by natural phenomena, the adequate ventilation of the shelter depends solely on the proper design (sizing and location) of inlets and outlets as well as the suitable orientation of the shelter. Buoyancy forces are negligible during the hot weather periods, namely summer. Therefore, ventilation rates rely heavily on the exposure and orientation of the building relative to prevailing winds.

To produce some guidelines for building orientation maximizing natural ventilation rates during the summer, weather data on prevailing wind (speed and direction) was used to compute the best building direction for 10 locations in the province of Ontario. This preferred building orientation was based on the minimum number of hours during which the summer ventilation rate was under that recommended.

Prevailing winds are the primary driving force for natural ventilation systems throughout the summer. Brockett and Albright (1987) have demonstrated that under low wind conditions of 0.5 m/s (1.8 km/h), buoyancy forces become significant only when an 8° C temperature differential exists between the inside and outside building environment. When prevailing winds are of the order of 3 m/s (10.8 km/h), temperature differential must exceed 14° C. Similarly, the neutral pressure concept (ASHRAE, 1993) indicates that summer wind velocities exceeding 0.75 m/s (1.7 km/h) will cause more natural ventilation than the stack effect created by typical summer temperature differentials of 3° C. This implies that natural ventilation inlets for summer ventilation must be designed based on prevailing wind conditions.

Wind induced natural ventilation rates resulting from prevailing winds can be approximated from a simple equation (ASHRAE, 1993):

$$Q = C_v A V \qquad (1)$$

where
Q = ventilation rate (m^3/s)
C_v = effectiveness of the opening
A = free area of inlet (m^2)
V = wind velocity (m/s)

Wind direction is accounted by the factor C_v, where values of 0.5 to 0.6 and 0.25 to 0.35 correspond to perpendicular and diagonal winds, respectively. This equation was tested against the survey data of swine barns during winter conditions and found to be adequate for the design of winter ventilation rates (Jedele, 1979).

Recent interest in improving the performance of natural ventilation systems has aroused concern about the accuracy of equation 1. Bruce (1975) proposed a method whereby the flow through inlets is computed as:

$$q_j = a_j * C_D V_{10} |Cp_j - Cp_i|^{3/2} / (Cp_j - Cp_i) \qquad (2)$$

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where

q_j – flow through opening j (m^3/s)
a_j – area of opening j (m^2)
C_D – discharge coefficient of 0.6 for sharp edge openings (dimensionless)
V_{10} – reference wind velocity measured at the standard meteorological height of 10 m (m/s)
Cp_j – external pressure coefficient for opening j
Cp_i – internal pressure coefficient

The unknown factors in equation 2 are Cp_i and Cp_j. The value for CP_i is determined from the continuity equation. The summation of all inlet and outlet flows must equal zero:

$$\sum_{j=1}^{n} a_j * |Cp_j - Cp_i|^{3/2} / (Cp_j - Cp_i) = 0 \quad (3)$$

The true value of CP_i, respecting equation 3, can be found by iteration.

The external pressure coefficient, Cp_j, is related to the prevailing wind measured at a height of 10 m as follows:

$$Cp_j = 2 * P / (\rho * V_{10}^2) \quad (4)$$

where

P – static pressure above atmosphere measured on the surface of the building component (Pa)
ρ – air density (kg/m^3)

For individual openings arranged in a continuous fashion and representing 27% of the area of both longitudinal walls of a symmetrical shelter, equation 2 provides natural ventilation rates which can be translated into C_v coefficients. This translation provides a simple design method using equation 1. The discharge coefficient, C_v, ranges from 0.19 to 0.40, depending upon wind direction. The following relation between prevailing wind angle and inlet C_D value was obtained for a naturally ventilated livestock shelter using panels along both long walls (Choinière, 1991):

$$C_v = 0.15 + 0.25 \ |\sin\theta| \quad (5)$$

for θ ranging from 10° to 170° and 190° to 350°

$$C_v = 0.19 + 0.02 \ |\sin 9 * (\theta - 170)| \quad (6)$$

for θ ranging from 170° to 190°

$$C_v = 0.19 + 0.02 \ |\sin[9 * (\theta - 10)]| \quad (7)$$

for θ ranging from 0 to 10. Aynsley et al. (1977) have demonstrated that equation 2 offers advantages:

- Ability to compute individual inlet flow based on the opening's position on the wall of the building relative to wind direction and velocity.
- Elimination of wind tunnel trials to predict the performance of various inlet distribution patterns.

The ventilation rate which prevails within a shelter during the summer under a specific prevailing wind condition (building orientation with respect to wind velocity and direction) can therefore be computed for a given building design. Furthermore, the effect of building orientation can be obtained simply by varying the coefficient C_v according to the relative direction of the wind. Preferred building orientation can be based on that having minimal effect on livestock performance or that giving the least time span of ventilation conditions under the required summer rate.

Methodology

A typical swine barn with panels and chimneys designed for adequate natural ventilation was selected for the experiment. The C_v values for the inlets and outlets of this building had been determined previously for all wind directions. A specific location in Ontario, namely Ottawa, was selected where meteorological wind data has been recorded on an hourly basis for 31.4 years. This wind data was used to calculate the ventilation rates occurring in the barn when temperatures exceeded 20° C. This temperature range is considered critical for the operation of summer ventilation rates (Esmay and Dixon, 1986). A ventilation rate was calculated for each hourly wind event corresponding to a temperature above 20° C. The ventilation rates were then subdivided in ranges using 1000 L/s increments and the frequency of occurances of each range was then compiled. The time span during which ventilation rates were under that required was compiled for statistical analysis. A nonparametric statistical method was then used to identify the specific building orientation giving the least interruption in summer ventilation rate. This procedure was repeated for two other ranges of temperatures, above 25° C and above 30° C, and for nine other locations in the province of Ontario (table 1).

The Experimental Barn

The C_v values used to calculate the natural ventilation rates were obtained previously from wind tunnel tests (Choinière, 1991). The model barn represented a typical gable-roofed piggery, 12.2-m wide × 24.4-m long with walls 2.7 m in height (fig. 1). The roof had a slope of 4/12. the ceiling was cathedral, and the eaves overhung the walls by 30 cm. The inlets consisted of 12 panels on both side

Table 1. Location and number of years of weather data accessed for each weather station

Location	Years of Data
Barrie	6.5
London	34.5
North Bay	34.4
Ottawa	34.4
Simcoe	5.4
St. Catherines	2.3
Toronto	34.5
Trenton	34.4
Waterloo	21.4
Windsor	34.5

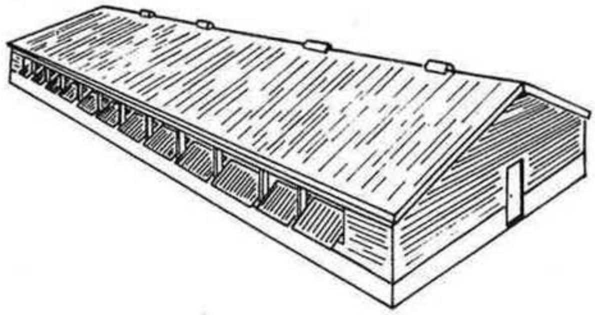

Figure 1–Model barn used for the calculations of natural ventilation rate.

walls, equivalent to 27% of the total wall area, and two end panels. The outlets consisted of four intermittent chimneys, each 60 cm × 60 cm.

The model barn was assumed to hold 340 grower hogs. It therefore required a minimum summer ventilation rate of 13.6 m^3/s or 40 L/s/hog.

Weather Data Processing

A computer program was conceived to calculate natural ventilation rates based on the building model, illustrated in figure 1, and wind data recorded by a weather station and sorted for temperature ranges above 20° C.

The wind data pertained to that collected by meteorological stations operated by Environment Canada. For each 10 weather stations studied (table 1), the meteorological data was sorted in order to obtain all wind events (speed and direction) which occurred for the three temperature ranges (+20° C, +25° C, and +30° C). Wind events were recorded on a hourly basis, for all the weather stations selected.

The computer program used to sort the data and to calculate the natural ventilation rate was written in Quick Basic. For each of the three sets of wind data classified according to temperature range (+20° C, +25° C, and +30°C), ventilation rate frequencies were calculated using, in turn, six building orientations measured clockwise parallel to the ridge, from the northerly direction: 0°, 30°, 60°, 90°, 120°, 150°. From the ventilation rate obtained for each hourly wind event, the frequency and consecutiveness of each specific ventilation range (0-1, 1-2, 2-3, . . ., 12-13 m^3/s) was compiled. Therefore, 18 sets of ventilation rate frequencies were computed for each of the 10 locations. Similarly, the time span during which the ventilation rate was under the required 13.6 m^3/s was calculated to keep track of the frequency of consecutive hours under the required summer ventilation rate.

Statistical Analysis

The data generated by the computer model was found to be quite similar between the six building orientation for all 10 stations studied. As a consequence, preferred building orientation could only be identified through the use of a statistical method.

A nonparametric statistical method was identified as appropriate for the analysis of a data generated from a simulation. The lack of association with a specific type of distribution provided a second reason for the selection of a nonparametric method. The procedure frequency was therefore used to test the building orientations. (SAS, 1987).

The nonparametric statistical analysis was carried out on the ventilation frequency data below the critical summer rate of 13.6 m^3/s. This range of ventilation rate was selected because it is the critical design parameter. The parameter used for the procedure frequency method (SAS, 1987) was the frequency of each 1000 L/s range of generated ventilation rate below 13.6 m^3/s, rather from 0 to 13.0 m^3/s.

The procedure frequency method consists of building a matrix where rows and columns are associated with building orientation and ventilation intervals, respectively. The parameter entered in each cell of the matrix is the frequency of the specific ventilation rate range associated with the building orientation. For each range of ventilation rate, the frequency of each six building orientations were summed and used to compute individual frequency percentages. A demonstration of this method is given in table 3. Thus, the matrix compares the relative frequencies for each building orientation, based on specific ventilation range. Once this matrix is built, Chi-Square values are computed and levels of significant differences are determined.

When analyzing the statistical data, the frequencies of the two ventilation rates 0 to 1 m^3/s and 1 to 2 m^3/s were not used. These frequencies were considered biased estimates because of the inadequate sensitivity of the anemometers used by the weather stations to accurately measure low wind speeds.

Results and Discussion

To simplify the presentation of the results, a complete set of analyses will be presented, based on the meteorological data of the weather station at the Ottawa airport and the temperature range exceeding 20° C. For this same station, the optimum building orientation for all three temperature ranges (+20° C, +25° C, and +30° C) will be compared. Finally, the optimum building orientation will be summarized for the 10 locations analyzed.

The frequencies of various levels of ventilation rates calculated from the meteorological data of the Ottawa airport weather station are illustrated by figure 2, for the +20° C range. For all six building orientations, the ventilation rate generally ranged from 7.0 m^3/s to 37.0 m^3/s. Table 2 presents the average ventilation rate, their standard deviation, and percentage of time below the summer design rate of 13.6 m^3/s for the period above 20° C. Comparison of ventilation rates for each building orientation provides more obvious results. The building orientation of 30° and 60° from the northerly direction gave the lowest ventilation rate or at least the longest percentage of time during which the ventilation rate does not meet the required summer level of 13.6 m^3/s. Nevertheless, the average ventilation rate for each building orientation demonstrated very large standard deviations (C.V. over 50%). The lack of obvious difference in ventilation rate among the six building orientations is further demonstrated by figure 3. This figure shows the frequency of various consecutive hours during which the animals are exposed to an insufficient ventilation rate. A

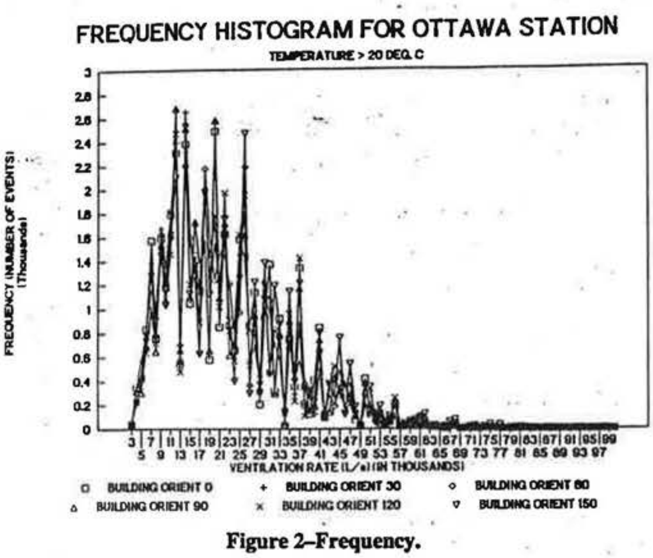

Figure 2–Frequency.

Table 3. Row percent values for ventilation rates below the minimum summer design level and building orientation*

Ventilation Rate (L/s)	Building Orientation 0°	30°	60°	90°	120°	150°	Total Row (%)
3 000	15.38	21.54	21.54	15.38	12.31	13.85	100
4 000	21.19	20.11	20.11	21.19	8.23	9.18	100
5 000	14.69	22.16	22.16	14.69	12.72	13.58	100
6 000	20.08	20.75	20.75	20.08	9.62	8.72	100
7 000	21.60	19.07	19.07	21.60	9.00	9.67	100
8 000	15.77	22.53	22.53	15.77	11.42	11.98	100
9 000	19.01	20.05	20.05	19.01	10.94	10.93	100
10 000	18.96	20.30	20.30	18.96	11.28	10.20	100
11 000	18.67	20.57	20.57	18.67	9.50	12.01	100
12 000	19.92	17.77	17.77	19.92	12.38	12.24	100
13 000	19.06	20.25	20.25	19.06	9.30	12.08	100
14 000	18.83	19.11	19.11	18.83	12.27	11.84	100

* Ottawa Weather Station and temperatures greater than or equal to 20° C.

nonparametric statistical analysis was therefore carried out to determine whether or not there is a significant difference in ventilation rates between all six building orientations.

The nonparametric statistical analysis for the ventilation rates calculated from the Ottawa weather station and for temperatures exceeding 20° C required the grouping of the results based on building orientation (table 3) and ventilation range. For the Ottawa weather data, the building orientations of 120° and 150° gave a significantly better performance or a ventilation rate with the least time span under the design level of 13.6 m^3/s. When the temperature range is changed to +25° C and +30° C, the 150° orientation gave the best and most significant ventilation rates (table 4).

The building orientation demonstrating significantly least time span with ventilation rates under the summer design level is summarized in table 4 for all 10 Ontario locations. A higher temperature produced a slight change in ideal orientation for locations such as London, Simcoe, and Toronto. This results from the fact that higher temperature ranges are not necessarily associated with the same wind conditions. Furthermore, some regions seem to have wind conditions which vary much more than others. Nevertheless, the ideal building orientation should probably be based on the +20° C range as, above this temperature, animals become affected by heat stress.

Despite the optimal orientation of a naturally ventilated building, some period of poor ventilation should be expected throughout the summer (table 5). The consecutive period of poor summer ventilation ranges from 6 h in St. Catherines to 36 h in London. Furthermore, the building will suffer from poor ventilation during 12% (North Bay) to 27% (Windsor) of the time, based on a summer span of June to September. Depending on the frequency of the longer consecutive spans, the animals may suffer from heat stress.

Conclusions

The analysis of meteorological data from 10 weather stations distributed over the province of Ontario shows that there are preferred building orientations. These orientations will minimize the summer period with natural ventilation rates below 40 L/s/hog.

Even by building livestock shelters in this preferred orientation, the grower should expect some periods during which the ventilation rate will not meet that required for summer when outside temperatures exceed 20° C. This time span of poor ventilation rate can correspond to 12 to 27% of the warm period assumed to run from June to September, inclusively. There is need for further research

Table 2. Ventilation rates obtained for temperatures above 20° C*

Building Orientation (Angle from North)	Average Ventilation Rate (m^3/s)	Standard Deviation (m^3/s)	Percentage of Time Under 13.6 m^3/s (%)
0	20.4	13.31	26.9
30	19.1	12.43	28.3
60	19.2	12.17	27.4
90	20.0	12.78	26.5
120	21.2	13.48	23.4
150	21.7	13.68	23.2

* Weather data of the station at the Ottawa Airport.
Note: Angle measured parallel to the building ridge.

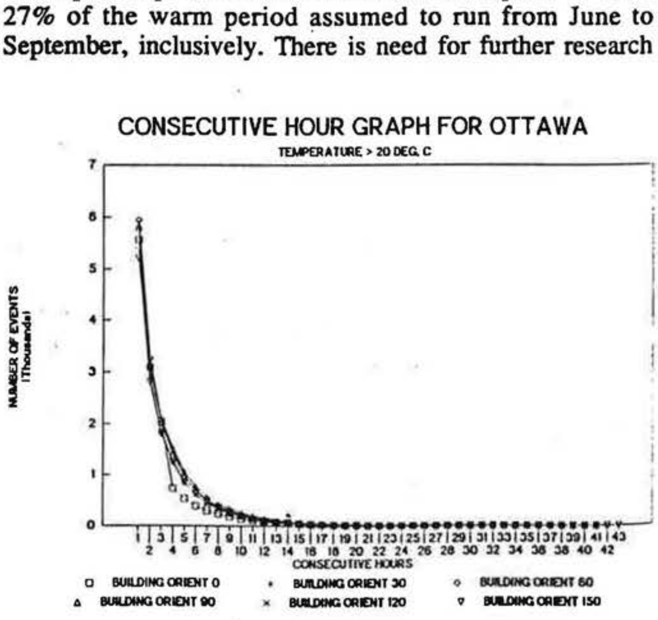

Figure 3–Consecutive.

Table 4. Preferred building orientation for 10 Ontario locations

Location	Preferred Building Orientation from North Temperature Range		
	+20° C	+25° C	+30° C
Barrie	60°, 90°	60°	30°
London	120°	150°	150°
North Bay	120°, 150°	150°	120°, 150°
Ottawa	120°, 150°	150°	150°
Simcoe	120°, 150°	30°, 150°	0°
St. Catherines	0°, 90°, 150°	0°, 90°	0°, 150°
Toronto	60°, 90°	120°	150°
Trenton	120°, 150°	120°	150°
Waterloo	150°	0°, 150°	0°
Windsor	120°	120°, 150°	120°

Table 5. Periods of poor ventilation for preferred building orientations*

Location	Building Orientation from North	Under-ventilated Period		
		Longest Consecutive Period (h)	Average Period (h/year)	Total Summer Period (%)
Barrie	90°	27	625	21
London	120°	36	755	29
North Bay	120°	21	345	12
Ottawa	150°	18	700	23
Simcoe	120°	15	760	29
St. Catnerines	150°	6	290	12
Toronto	90°	18	720	24
Trenton	120°	22	620	21
Waterloo	150°	11	365	12
Windsor	120°	34	815	27

* Temperatures above 20° C.

to evaluate if these low rates do actually occur and, if so, to evaluate their economical impact on the livestock. The effect is certainly a function of the frequency of the event and the number of consecutive hours.

The weather data used for this study was measured at weather stations located in wide open spaces. Furthermore, the ventilation rates were based on one type of building as well as a single concept of natural ventilation inlets and outlets. Wind obstructions, as may be found on typical farm sites, can further limit the time span during which the building is properly ventilated. The study should therefore be repeated with other types of natural ventilation systems to try and minimize the period with poor ventilation.

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References

ASHRAE. 1993. *Handbook of Fundamentals*, 343-345. Atlanta, Ga.: American Society for Heating, Refrigeration and Air Conditioning Engineering.

Aynsley, R. M., W. Melbourne and B. J. Vickery. 1977. *Architectural aerodynamics*. Applied Science Publishers Ltd., London, England.

Brockett, B. L. and L. D. Albright. 1987. Natural ventilation in single airspace buildings. *J. of Agric. Eng. Res.* 37:141-154.

Bruce, J. M. 1975. A computer program for the calculation of natural ventilation due to wind. *Farm Building Res. and Development Studies* 7:1-3, 6.

Choinière, Y. 1991. Wind induced natural ventilation of low-rise buildings for livestock housing by the pressure difference method and concentration decay method. M.S. thesis, University of Ottawa, Dept. of Civil Engineering, Ottawa, Canada.

Esmay, M. L. and J. E. Dixon. 1986. *Environmental Control for Agricultural Buildings*. Westport, Conn.: AVI Publishing Co. Inc.

Hellickson, M. A. and J. N. Walker. 1983. *Ventilation of agricultural structures*, 80-102. St. Joseph, Mich.: ASAE.

Jedele, D. G. 1979. Cold weather natural ventilation of buildings for swine finishing and gestation. *Transactions of the ASAE* 22(3):598-601.

SAS Institute. 1987. Statistical guide to SAS, Version 6th Ed. Cary, N.C.