Similitude Analysis of Ventilation by the Stack Effect from an Open Ridge Livestock Structure

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ABSTRACT

A similitude approach was used to develop predictive graphs for the ventilation rate due to the stack or chimney effect. Using a half scale model of an open side wall structure with a continuous and unrestricted open ridge, it was found that (a) ventilation rate was approximately proportional to ridge outlet width; (b) outlet Reynolds number response, i.e., ventilation rate, to changes in Grashof number was a function of the ratio between building height and ridge width.

INTRODUCTION

While natural ventilation is the oldest form of ventilation known, design and research has for the most part concentrated on mechanical ventilation. Natural ventilation can be divided into two types: (a) wind induced and (b) temperature induced. For buildings which depend totally on wind effects and temperature differences to provide sufficient ventilation for the housed animals, the primary design concern should be the amount of natural ventilation which occurs when wind speeds approach zero. That is, when a noticeable wind is present most structures will ventilate sufficiently when the side and/or end walls are opened. However, when the wind ceases, the geometry of the strucutral design should still provide or allow a satisfactory ventilation rate by the stack effect, i.e. flow caused by temperature differences between the inside and outside of the structure. Presently, there is a lack of satisfactory data available to predict the stack effect on ventilation rate in livestock structures.

REVIEW OF PREVIOUS WORK

When the air inside a structure is warmer than the outside air, air will enter the structure through planned or unplanned inlets and leave through outlets at higher elevations. If an inviscid, incompressible fluid is assumed, the Bernoulli energy equation can be used to predict the outlet velocity (Shepherd, 1965):

$$V = \sqrt{2gh\,\frac{(\rho_o - \rho_i)}{\rho_i}} \qquad [1]$$

(All symbols are defined in the List of Symbols). Since air flows are not inviscid but incur energy losses due to viscous effects, a correction is made to equation [1] by using a coefficient to account for all the energy losses between inlet and outlet

$$V = C\sqrt{2gh\,\frac{(\rho_o - \rho_i)}{\rho_i}} \qquad [2]$$

The problem in predicting ventilation rates due to stack effect is that the coefficient in equation [2] is unknown. Bruce (1977a, 1977b) has developed predictive equations based on heat production and building characteristics, but had assumed a coefficient, usually 0.5. Albright (1978) in studies of air flow through baffled, slotted inlets found coefficients as low as 0.2 while Shepherd (1965) gives a coefficient of 0.98 for well designed nozzles. Thus, the ventilation rate could vary significantly depending upon the coefficient, C, which actually occurs for a structure in question.

Attempts to develop predictive relationships for natural ventilation have usually centered around model studies (Dybwad and Hellickson, 1970; Froehlich and Hellickson, 1975; Koenig et al., 1977; Restropo and Manbeck, 1974) which have been dictated because of the lack of control in a natural setting. The above studies which attempted to analyze both wind and temperature difference effects have led to general suspicion of model studies, perhaps stated most succinctly by Bodman (1976):

> "...much of the research conducted to date (referring to natural ventilation) has been done on scale models which are not believed to provide realistic results."

The above model studies have introduced distortion. Thus, when ventilation rates were predicted for prototype systems, the unrealistic results mentioned by Bodman were obtained. However, a similitude study in which unaccounted distortion is not introduced, should be a viable means through which accurate prodictive relationships can be developed.

Given the lack of predictive relationships or design graphs for natural ventilation by the stack effect in any type of livestock structure, the present study focused on one distinct but common building type, an open ridge structure with the sidewall openings large compared to the ridge width opening.

OBJECTIVE

Develop predictive relations or graphs for the ventilation rate due to the stack effect from an open ridge livestock structure.

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ANALYSIS

The geometry of the structure modelled and analyzed is shown in Fig. 1. The ventilation rate through the structure due to the stack effect is given by:

$$Q = V_1 D_1 L \quad \ldots\ldots \quad [3]$$

For generality, consider the ventilation rate per unit length of ridge opening

$$\frac{Q}{L} \text{ or } q = V_1 D_1 \quad \ldots\ldots \quad [4]$$

The unit ventilation rate for a strucutre whose geometry is depicted by Fig. 1 is assumed to be a function of the following variables:

$$q = f_1 (D_1, D_2, h, \Delta T, T_0, \nu, g) \quad \ldots\ldots \quad [5]$$

With eight dimensional variables and three basic dimensions used, LTθ, the Buckingham Pi theorem requires five independent and dimensionless Pi terms. However, if a general differential equation for free convection is inspected

$$\frac{u\partial u}{\partial x} + \frac{v\partial v}{\partial y} = \frac{\partial}{\partial y} \nu(\frac{\partial u}{\partial y}) + u_e \frac{du_e}{dx} - g\beta(t-t_e) \quad \ldots\ldots \quad [6]$$

where x is along a streamline and y is measured normal to direction x (Eckert and Drake, 1972), it is seen that the gravitational effect enters in only one term, i.e. ($g\beta\ \Delta T$) which is equivalent to $g\Delta T/T_o$*. Therefore, rewriting equation [5] as:

$$q = f_2 (D_1, D_2, h, \nu, g\beta_0 \Delta T) \quad \ldots\ldots \quad [6]$$

which has six dimensional quantities with two basic dimensions, LT, requires four Pi terms as opposed to five previously:

$$\pi_1 = f_3 (\pi_2, \pi_3, \pi_4) \quad \ldots\ldots \quad [7]$$

*For the case of constant pressure and for a perfect gas, the gas expansion coefficient, β, can be shown to be equivalent to the inverse of absolute temperature.

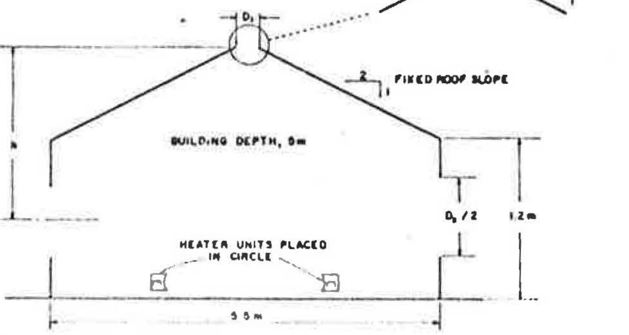

FIG. 1 Variables considered as affecting natural ventilation due to stack effect. Sketch of an open ridge livestock structure and dimensions of model used in present study.

where

$\pi_1 = V_1 D_1/\nu$ (Reynolds number, Re)

$\pi_2 = g\beta\Delta T h^3/\nu^2$ (Grashof number, Gr)

$\pi_3 = D_1/h$ (ratio of ridge exhaust width to fluid acceleration distance)

$\pi_4 = D_2/h$ (ratio of inlet width to fluid acceleration distance)

Jakob and Hawkins (1957) present an alternative argument for the above formation of Pi terms. Restricting the study to the above variables requires the following assumptions and restrictions:

1 outside wind conditions are still air, i.e. no wind effects are considered;

2 compressibility effects due to air velocity are negligible;

3 the ridge outlet is long enough to behave as an infinitely long opening;

4 the difference between inside and outside viscosity does not affect the flow;

5 obstructions within the structure do not affect the overall ventilation rate; and

6 the temperature difference term, ΔT, completely accounts for the thermal characteristics of the building as well as the heat production rate of the animals; that is any heat added to the building via solar radiation, heat conducted through the walls or heat produced within the building all serve to raise inside air temperature and therefore a variable formed from the difference between inside and outside air temperatures represents the potential for ventilation by stack effect.

The final choice of Pi terms did not include the inverse Archimedes Number, $V^2/g\beta\Delta Th$, or the Froude Number, V^2/gh, which was precluded by the final choice of dimensional variables, i.e. $g\beta\Delta T$ as opposed to g, β and ΔT. The Reynolds Number was chosen as the dependent variable because it is the unit flow rate, q, divided by kinematic visocity, ν, whereas the Archimedes Number or a Froude Number does not relate directly to the primary dimensional variable of interest, q.

To circumvent the problem associated with the introduction of distortion, a true model study was performed which requires

$$(\pi_j)_m = (\pi_j)_p \text{ for } j \neq 1 \quad \ldots\ldots \quad [8]$$

If the design requirements imposed by equation [8] are satisfied, then it directly follows that

$$(\pi_1)_m = (\pi_1)_p \quad \ldots\ldots \quad [9]$$

Usually no difficulty arises in satisfying equation [8] except for the Grashof Number which for the case when air is used in the model requires the following temperature scaling

$$(\Delta T)_m = n^3 (\Delta T)_p \quad \ldots\ldots \quad [10]$$

In a naturally ventilated structure, a 1 to 3 °C temperature difference between inside and outside air would be expected or at least desired during the summer time. For a length scale of two, which was used in this study, a 8 to 24 °C ΔT is required in the model to represent the prototype temperature condition without distortion. The above temperature differences defined by a length scale of two are already at the limits of experimental capabilities. Thus, the use of smaller models and larger length scales would lead to the introduction of distortion which would have to be evaluated before any meaningful interpretation could be given the experimental findings.

EXPERIMENTAL PROCEDURE

Design recommendations and predictive relations for ventilation rate were obtained from a model as depicted in Fig. 1, which was modeled after a typical free stall dairy or beef barn. The model measured 5.5 m (18 ft) in width and 5 m (16 ft) in length. The inlet widths ($D_2/2$) were fixed at 0.6 m (2 ft) since the primary design concern addressed was summer time ventilation when maximum ventilation is used and a large inlet area would be employed. The effect of restricting the inlet opening area was not addressed. The roof slope was fixed at 6 in 12, which is steeper than most agricultural roof slopes, to increase h and thus the natural ventilation through the building. The ridge outlet size was varied by extending or removing part of the roof such that outlet geometry and roof slope always remained the same. The walls and roof were formed with wood framing and rigid board insulation with all joints taped.

Air temperature measurements were accurate to $\pm$ 0.3 °C and were obtained using two copper-constantan thermocouples at each inlet and each outlet. Velocities were measured using a constant temperature hot wire anemometer with a signal linearizer (TSI - 1050 series model) and a true RMS voltmeter. The system was capable of continuously integrating the output of the velocity pobe tip to provide an accurate measurement of mean velocity. The probe tip used was capable of measuring velocity fluctuations up to 10 Hz with no attenuation in the signal. The velocity probe was placed 1/4 diameter, 0.25 $\times$ D_1, downstream from the ridge edge, see Fig. 1. The velocity term contained in the outlet Reynolds number was assumed to be 95 percent of the velocity recorded to account for the vena contracta effect (assumes minimum diameter of jet, 0.78 D_1, occurs one diameter downstream).

The heat source used to raise inside air temperatures was seven electrical resistance heaters with a total capacity of 10 kW (34,000 Btu/h) with four of the heaters having small mixing fans. The heater units were placed to form roughly a three meter circle on the concrete floor of the model structure. Temperature was varied by turning units on or off, and was the primary means by which the Grashof Number was varied.

No variation was observed in velocity recordings taken along several points of the inlets and the outlet. This suggests that the flow could be considered two dimensional at both the inlet and outlet. Foerthmann (1934) gives 20 as the aspect ratio necessary to assure two simensionality for flows issued from finite slot lenghts. The aspect ratio of the model ridge slot varied from 8 to 48; thus, Foerthmann's criterion was not always met. However, the predictions of ventilation rate per unit of building length would be conservative since the end walls effects would tend to decrease the flow due to frictional drag.

Data were taken in the following ranges of independent Pi terms to cover the expected range of operating conditions and designs prevalent in naturally ventilated livestock structures with a fixed geometry:

$$1.5 \times 10^9 \leq Gr \leq 7.5 \times 10^9$$

$$0.047 \leq \frac{D_1}{h} \leq 0.35$$

$$0.66 \leq \frac{D_2}{h} \leq 0.70$$

Test data are summarized in Tables 1 and 2.

RESULTS

The Reynolds number as a function of Grashof number for different ridge openings is shown in Fig. 2. The results indicate that the ventilation rate is approximately proportional to the width of the ridge opening for the widths studied. This finding is analogous to the commonly held assumption that flow rate through a slotted inlet is linearly related to slot width for a given pressure difference (Albright, 1978).

It is also apparent from Fig. 2 that the ratio of the ridge opening to ridge height, D_1/h, dramatically affects response of the Reynolds number to Grashof number changes. At D_1/h values of 0.083 and less, the outlet Reynolds number is essentially unaffected by increases in Grashof number. In previous model studies reported by Koenig et al. (1978) the Reynolds number was unaffected by changes in the Grashof number using a ridge design with an estimated D_1/h ratio of 0.03. However, in the present study, it was found as shown in Fig. 2 that the Reynolds number became increasingly responsive to the Grashof number as the ridge outlet size was increased at a fixed h. Therefore, to promote natural ventilation through ridge design requires a D_1/h ratio of 0.17 or more. For smaller D_1/h ratios, Fig. 2 strongly suggests the temperature difference between inside and outside air temperature could increase without causing a corresponding increase in ventilation rate.

DISCUSSION

The applicability of the design data provided by Fig. 2 should be addressed. In a strict sense the design data presented is only directly applicable to a prototype structure in which the geometry is identical to the geometry depicted by Fig. 1. However, the applicability can be extended by the following analysis of the physical effects of roof slope, inlet area, and Grashof number range. A prediction in these cases should be made with some reservation.

Roof Slope

The model study was for a 6 in 12 roof slope while

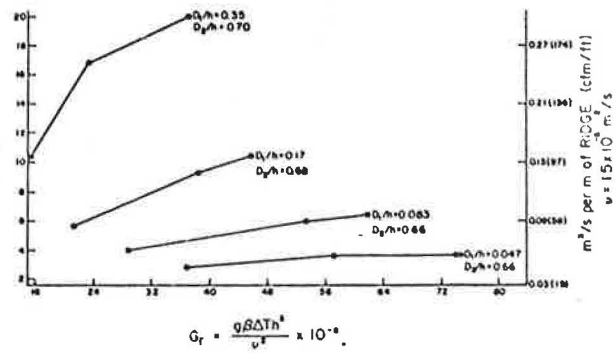

FIG. 2 Reynolds Number, π_1, as a function of Grashof Number, π_2, at various levels of ridge width to height ratios, D_1/h, and at a nearly constant inlet width to ridge ratio, D_2/h = 0.68 $\pm$ 0.22.

TABLE 1. GEOMETRIC CONDITIONS FOR INDIVIDUAL TESTS

Test #	h mm (in.)	D_1 mm (in.)	D_2 mm (in.)	$\pi_3 = D_1/h$	$\pi_4 = D_2/h$
1	1850 (73)	88 (3.5)	1220 (48)	0.047	0.66
2	1830 (72)	152 (6)	1220 (48)	0.083	0.66
3	1790 (70)	305 (12)	1220 (48)	0.17	0.68
4	1730 (68)	610 (24)	1220 (48)	0.35	0.70

other common roof slopes are 3, 4, or 5 in 12. There are three primary ways in which energy is lost in the flow: turbulent energy losses due to a rapid expansion at the inlet, drag losses along the walls, and losses due to fluid separation along walls and roof approaching the ridge outlet. For flows into exhaust hoods, the energy (head) losses are fairly constant (Hemeon, 1963, pg 357) with an approximate variation of only 25 percent in velocity head loss between a flanged duct opening (180 deg included angle) and an exhaust duct with a 10 deg included angle taper.† Therefore, the difference in flow rates between a 3 in 12 or 6 in 12 roof slope would not be expected to be great. Consequently, curves presented in Fig. 2 could be extended to provide a reasonable prediction for the natural ventilation rates of open ridge structures with roof slopes different from 6 in 12.

Inlet Area

All data were collected with a fixed inlet width, i.e. π_3 held nearly constant. Again, the results presented in Fig. 2 can only be used without qualification to other structures in which the ratio of D_2/h is also 0.68. The energy losses at the inlet can be characterized by losses which occur in duct flow for a rapid expansion. The energy loss is not due to the viscous effects of drag (friction losses), but is due to the viscous effect that creates vorticity or rotational motion. The energy in the vortices (eddies) is eventually dissipated by viscosity and is not available to accelerate the fluid out the ridge opening. For rapid expansions, the head loss is approximately one dynamic head, i.e. $V_2^2/2$, if the air stream discharges into a large downstream area when the velocity is effectively zero. Since this is normally the situation in an animal structure, it could be concluded that Fig. 2 results may be applied regardless of inlet width. However, as the inlet width becomes larger compared to the ridge width, the velocity through the inlets also approaches zero. Thus, even though the Reynolds number of the inlets (V_2D_2/ν) would be the same as the Reynolds number at the outlet, the energy loss at the inlet would approach zero. That is, the flow of air through an inlet of large width in which the velocity approaches zero begins to act like a potential flow for an ideal fluid in which no energy loss would be incurred. Therefore, the data should not be extended for ratios of D_1/D_2 greater than 1/2 (the maximum ratio in this study).

Grashof Number Range

When the expected Grashof number is beyond the range covered by Fig. 2, extrapolation should be done with extreme caution and is not recommended for D_1/h ratios greater than 0.09. Many structures have D_1/h ratios less than 0.09 and, therefore, the trends of the curves in Fig. 2 should be inspected to see if the results might be extended to higher Grashof numbers. Inspection of Fig. 2 does, in fact, reveal that the Reynolds number for small D_1/h ratios remain nearly constant for the entire range of Grashof numbers tested. It is then reasonable to assume for D_1/h ratios less than 0.09 that further increases in the Grashof number would not significantly change the outlet Reynolds number. For design purposes, if the D_1/h ratio is less than 0.09, a constant Reynolds number or ventilation rate can be assumed regardless of the Grashof number or the magnitude of ΔT.

Working Example: The application of the results presented in Fig. 2 is perhaps best illustrated by example. Consider an open ridge beef barn with open side walls with the following characteristics: ridge opening width 0.174 m; ridge height (floor to ridge) 5 m; side wall inlets 1.25 m centered 1.3 m from floor; temperature difference desired between inside and outside 1 °K. Assuming air properties of $\nu = 1.5 \times 10^{-5}$ m²/s (1.6×10^{-4} ft²/s), $\beta = 1/300$ °K (1/540 °R) and gravitational constant of 9.8 m/s², the expected Grashof number (π_2), ridge width to height ratio (π_3), and inlet width to height ratio (π_4) are:

$$\pi_2 = \frac{g\beta\Delta T h^3}{\nu^2} = \frac{(9.8\ \frac{m}{s^2})(\frac{1}{300\ ^\circ K})(1\ ^\circ K)(5 - 1.3\ m)^3}{(1.5 \times 10^{-5}\ m^2/s)^2} = 74 \times 10^8$$

†If the included angle were 0 deg, then the walls would be parallel.

TABLE 2. REYNOLDS NUMBERS, GRASHOF NUMBERS, MASS FLOW AND PERTINENT DIMENSIONAL DATA FOR GEOMETRIC CONDITIONS DESCRIBED BY TABLE 1.

Test #	Re	Gr(10^{-8})	V_1 (ms^{-1})	ΔT (°K)	T_1 (°K)	ν ($mm^2 s^{-1}$)	ρq* ($kg\ s^{-1}\ m^{-1}$)
1	2680	36.7	0.49	4.4	302.2	15.9	0.047
	3570	56.9	0.66	7.2	305.1	16.2	0.063
	3700	74.0	0.70	9.7	307.9	16.5	0.066
	3780	74.9	0.71	9.8	308.0	16.5	0.067
2	3970	29.0	0.41	3.5	299.8	15.7	0.069
	6070	53.3	0.64	6.8	303.6	16.0	0.107
	6420	61.7	0.68	7.9	304.6	16.1	0.113
3	5800	21.1	0.30	2.8	300.5	15.7	0.101
	9190	38.5	0.48	5.2	303.2	16.0	0.162
	10,560	45.8	0.56	6.3	304.7	16.1	0.187
4	10,230	14.6	0.26	2.1	298.5	15.5	0.177
	16,770	23.5	0.43	3.4	300.2	15.7	0.292
	19,980	37.2	0.52	5.4	301.4	15.8	0.350

*Density assumed dry inside air.

$$\pi_3 = D_1/h = \frac{0.174 \text{ m}}{(5 - 1.3) \text{ m}} = 0.047$$

$$\pi_4 = D_2/h = \frac{2(1.25 \text{ m})}{(5 - 1.3 \text{ m})} = 0.68$$

Using Fig. 2, the Reynolds number is estimated as 3700 or:

$$q(\frac{m^3}{s\text{-}m}) = (\pi_1)(\nu) = (3700)(1.5 \times 10^{-5} \text{ m}^2/s)$$

$$= 0.055 \text{ m}^3/\text{s-m} \ (35 \text{ cfm/ft})$$

The total ventilation provided would be q times the length of the ridge opening. For design purposes, the equilibrium air temperature would be determined through an iterative procedure of balancing the heat being produced with the heat lost by convection (ventilation), conduction and radiation.

FUTURE WORK

The current study was an undistorted model study of a "to be built" naturally ventilated poultry house. Although similitude theory relates model results to prototype performance, confidence can always be increased by actual comparisons between model and full scale building performance. A broiler house had been built which will allow such a comparison. Also, a study is currently under way which addresses the problem of distortion effects in natural ventilation model studies, the objective of which is to develop a set of prediction fators for a distorted model study.

CONCLUSIONS

Experimental results obtained from a 1/2 scale model of an open ridge livestock structure show

1 Ventilation rate is approximately proportional to the ridge outlet width for a fixed ridge height and a fixed temperature difference, i.e. Re α D_1/h for a fixed Grashof number.

2 For small ridge width to building height ratios, e.g. ridge openings of 300 mm (12 inches) and heights of 3.6 m (12 feet), the ventilation rate through the ridge does not significantly increase as the difference between inside and outside air temperature increases; i.e. Re α Gr^b where $b \cong 0$ for $D'/h \leqslant 0.1$.

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LIST OF SYMBOLS

C	coefficient for friction and turbulent energy losses from inlet to outlet, dimensionless
D_1	ridge exhaust width, m
D_2	inlet width (sum of both inlet widths), m
g	acceleration of gravity, m/s²
Gr	Grashof number
h	vertical distance between inlet and outlet, m
L	length of ridge slot, m
n	length scale, dimensionless
Q	ventilation rate, m³/s
q	ventilation rate per unit length of ridge outlet, m³/s-m
Re	Reynolds number
u	velocity in the x direction, m/s
v	velocity in the y direction, m/s
V	characteristic velocity associated with h, m/s
V_1	exhaust air velocity, m/s
V_2	velocity at inlet, m/s
x	a spatial direction, m
y	a Spatial direction, m
β	gas expansion coefficient for outside air, $°K^{-1}$
ΔT	difference in inside and outside air temperature, °K
ν	kinematic viscosity of inside air, m²/s
π	a dimensionless variable
ρ	density of air, kg/m³

Subscripts

e	refers to fluid outside the effects of buoyancy
i	inside
j	refers to any of the four Pi terms
m	model
o	outside
p	prototype