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A COMPUTER MODEL FOR CONTROLLING NATURAL VENTILATION

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SUMMARY:

A natural ventilation control strategy that promotes airflow uniformity and employs an algorithm that calculates the natural ventilation rate based on combining pressure differences caused by thermal buoyancy and wind forces is incorporated into a control program.

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A COMPUTER MODEL FOR CONTROLLING NATURAL VENTILATION

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INTRODUCTION

Natural ventilation systems require less energy and maintenance and are quieter than mechanical ventilation systems. Natural ventilation is powered by the wind and heat generated inside the building, whereas mechanical ventilation is powered by electrical fans. In New York state, an operator of a dairy farm could save $12/cow-yr (at $0.10 kwh) if the cow barn has natural ventilation instead of mechanical ventilation with barn temperatures equivalent for either system.

Why is natural ventilation not used more widely? A major reason is that a natural ventilation system lacks control of the airflow through the building, thereby lacking control of temperature inside the building. Yet, with the advent of microprocessors for continuous monitoring and control, and sensors that are accurate yet inexpensive, control of the ventilation rate in a natural ventilation system may no longer be a problem.

Currently, automatically controlled natural ventilation systems are being used in animal housing. One example is a setup developed by the Scottish Farm Buildings Investigation Unit. This system is for a swine building with eave openings, a dampered chimney, and adjustable sidewall vents. The sidewall vents are opened or closed to achieve a desirable air temperature inside the building (Bruce, 1979).

The disadvantage of this system is that the leeward vent and windward vent are always open the same amount. For low wind speeds, having the leeward vent open wider than the windward vent might result in more complete mixing within the building than if both vents are equally open. In a situation where the wind force along a wall is not uniform, having three sidewall openings adjusted separately might also result in more complete air mixing than having a single opening adjusted as a unit.

The goal of this work was to investigate a natural ventilation control strategy that promotes airflow uniformity and employs an algorithm that calculates the natural ventilation rate based on combining pressure differences caused by thermal buoyancy and wind forces.

VENTILATION CRITERIA

The desired ventilation rate of a building can be determined based on an optimum temperature, a maximum humidity, or a tolerable contaminant concentration. In most agricultural applications, temperature control is the critical factor in determining the required airflow. However, during very cold weather, humidity and contaminant control may be the critical factors.

A steady-state energy balance is normally used to calculate ventilation for temperature control. To maintain a constant inside temperature, the heat produced within the building must equal the heat losses. Heat is added to a building from animal metabolism, solar energy, and mechanical devices. When the outside temperature is less than the inside temperature, heat is conducted through the walls and roof. Additional heat is exhausted when ventilating. The ventilation rate is calculated to balance the heat gains and losses.

$$Q = (SOLAR + ANIMAL + MECH - LOSS)/(c_p \Delta T \rho_o) \quad (1)$$

where

Q = ventilation rate required by the energy balance, m^3/s
c_p = specific heat of air (1006.0 J/kg K)
ΔT = difference between inside and outside air temperatures, K
ρ_o = density of outside air, kg/m^3
SOLAR = sensible heat gain due to solar energy, W
ANIMAL = sensible heat produced by animals, W
MECH = sensible heat produced by lights and machines, W
LOSS = sensible heat lost through the building shell, W.

The sensible solar gain through each building surface is calculated by:

$$SOLAR = \sum_{n=1}^{k} I_n \, t_n \, AREA_n \, PS \quad (2)$$

where

k = the number of surfaces
I_n = insolation measured at surface n, W/m^2
t_n = transmittance of surface n
$AREA_n$ = area of surface n, m^2
PS = fraction of total heat gain that is sensible heat

Sensible heat production from animals decreases with an increase in air temperature. Albright (1974) uses the following to approximate sensible heat production over narrow temperature ranges:

$$ANIMAL = au\ (\beta + \gamma T_{in}) \quad (3)$$

where

au = the number of animal units in the building
β = sensible heat production per animal unit at inside temperature of 0 C, W/animal unit
γ = temperature factor to adjust sensible heat production, W/animal unit - C
T_{in} = inside temperature, C

Values for β and γ can be determined from data standard D270.4 in the Agricultural Engineers' Yearbook (1984). For example, β = 1840 W/1000 kg and γ = -35.5 W/1000 kg - C for mature dairy cattle exposed to an air temperature between -7 to 20 C.

Heat losses by conduction through walls and roofs are proportional to the effective temperature difference between inside the barn and outside. The effective ambient temperature depends on the outside air temperature, solar gains, and thermal radiation. The ASHRAE Handbook of Fundamentals (1981) uses the concept of sol-air temperatures as the effective outside temperatures to include solar absorption gains and radiation losses in calculating the conductive heat loss. Sol-air temperature is calculated by

$$(T_{sol\text{-}air})_n = T_{out} + (\alpha_n I_n - \varepsilon_n \Delta R_n)/ho_n \tag{4}$$

where

$(T_{sol\text{-}air})_n$ = sol-air temperature on surface n, C
T_{out} = outside air temperature, C
α_n = solar absorptivity of surface n
I_n = solar insolation on surface n, W/m^2
ε_n = long-wave thermal emissivity of surface n
ΔR_n = net thermal radiation exchange of a black body due to long wave reradiation, W/m^2K
ho_n = convective coefficient of surface n, W/m^2K

The factor, ΔR, depends on the angle of the surface. For clear sky conditions

$$\Delta R_n = \cos(\sigma_n) \tag{5}$$

where

σ_n = tilt angle of surface n, measured from the horizontal.

Using the sol-air temperature, the conductive heat loss through the walls and roof of a building is given by:

$$LOSS = \sum_{n=1}^{k} AREA_n\, U_n\, (T_{in} - T_{sol\text{-}air})_n \tag{6}$$

where

U_n = unit thermal conductance of the surface, W/m^2K

After calculating the sensible heat gains and losses, the ventilation rate required to maintain a constant temperature can be determined using the steady-state energy balance (equation 1).

The ventilation rate required to remove contaminants is (ASHRAE, 1981)

$$Q = F/(C_i - C_o) \tag{7}$$

where

- Q = minimum ventilation rate, m^3/s
- F = generation rate of contaminants, kg/s
- C_i = acceptable concentration of contaminants in the building environment, kg/m^3
- C_o = concentration of contaminants in the outside air, kg/m^3.

A moisture balance is used to determine the minimum airflow to control humidity. To keep a constant inside air moisture level, the rate of the moisture exhausted must equal the rate of moisture produced. From this balance the ventilation rate is given by

$$Q = \dot{m}/(\rho_o(W_{in} - W_{out})) \tag{8}$$

where

- $\dot{m}$ = rate of water evaporated, kg/s
- ρ_o = density of outside air, kg/m^3
- W_{in} = maximum acceptable humidity ratio of exhausted air
- W_{out} = humidity ratio of outside air.

NATURAL VENTILATION MODEL

Introduction

The driving forces of a natural ventilation system are thermal buoyancy and wind. The hydrostatic pressure caused by thermal buoyancy and the aerodynamic forces of the wind create pressure differences across openings in a building. Air flows from a higher pressure area to a lower pressure area, hence, ventilation.

Thermal buoyancy has little effect on natural ventilation when the wind is strong. When the wind is calm, thermal effects prevail. There is no clear demarcation where dominance passes from one effect to the other. Jardinier (1980) recommended wind forces be used to determine infiltration when the average wind speed is above 2 m/s. Dick and Thomas (1951) developed the following guideline to determine whether natural ventilation would be driven predominantly by wind or thermal buoyancy:

$$C = \log(V^{*2}/(T_{in} - T_{out})) \tag{9}$$

where

V^* = wind velocity, mph

T_{in} = inside temperature, °F

T_{out} = outside temperature, °F

If C is less than 0.3, thermal buoyancy is the predominant force. If C is greater than 0.3, wind predominates.

However, there will be times when both wind and thermal effects contribute. The procedure recommended in the ASHRAE Handbook of Fundamentals (1981) combines the thermal-induced and wind-induced airflow by quadrature.

$$Q = \sqrt{Q^2_{thermal} + Q^2_{wind}} \tag{10}$$

It is not clear that this simple model is accurate when thermal and wind effect are approximately equal, or when airflow through cracks or porous walls is not proportional to the square root of the pressure difference.

Analysis

The approach which will be used to calculate combined natural ventilation is to add (at every opening) the pressure difference due to wind to the pressure difference due to thermal effects, and calculate the resulting airflow. Aerodynamic pressure differences across an opening in a building wall can be calculated using the following equation:

$$\Delta P_{wind} = 1/2\ \rho_o\ V^{*2}\ (cp_o - cp_i) \tag{11}$$

where

ΔP_{wind} = pressure difference due to wind force, Pa

ρ_o = density of outside air, kg/m^3

V^* = velocity of wind, m/s

cp_o = outside wind pressure coefficient

cp_i = inside wind pressure coefficient

For a system with continuous monitoring and control, wind pressure differences can be measured directly.

Pressure differences driven by thermal buoyancy can also be determined. Bruce (1977) calculates the airflow through an opening due to hydrostatic pressures using a neutral pressure level as a reference point. The neutral pressure level, $\bar{h}$, is the height at which the pressure difference caused by thermal buoyance is zero.

$$\Delta P_{Thermal} = g\ (\rho_o - \rho_i)\ (\bar{h} - h) \tag{12}$$

where

$\Delta P_{thermal}$ = pressure difference due to thermal buoyancy, Pa
g = acceleration due to gravity, 9.8 m/s^2
ρ_o = density of outside air, kg/m^3
ρ_i = density of inside air, kg/m^3
$\bar{h}$ = height of the neutral pressure level with respect to the ground, m
h = height of the opening with respect to the ground, m

For a building with a large ridge vent, $\bar{h}$ is located near the ridge. For a building with large openings at the base, $\bar{h}$ is located near the base (figure 1a,b).

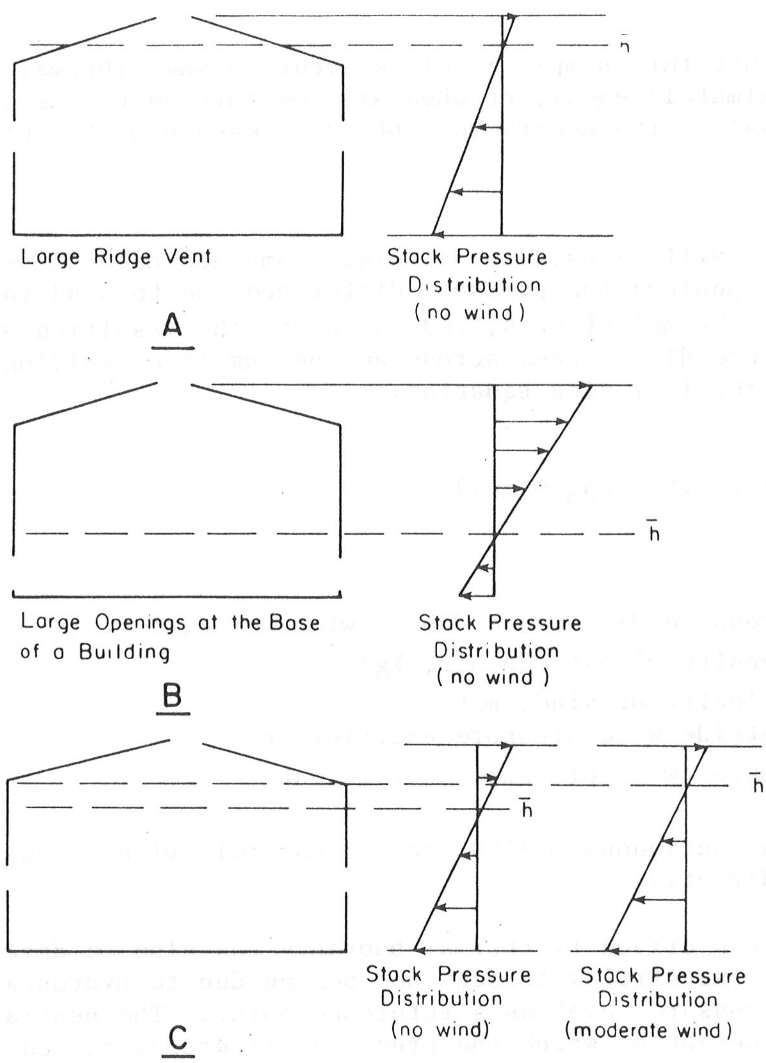

Figure 1. Neutral pressure level.

Superimposing wind-induced and thermally-induced pressure differences results in the following equation:

$$\Delta P_{total} = \Delta P_{thermal} + \Delta P_{wind} \tag{13}$$

$$\Delta P_{total} = g(\rho_o - \rho_i)(\bar{h} - h) + 1/2\ \rho_o\ V^{*2}\ (c\rho_o - c\rho_i) \tag{14}$$

where

ΔP_{total} = total effective pressure difference, Pa.

The neutral pressure level, $\bar{h}$, is affected by the wind forces. It increases for moderate wind speed and a building with a ridge vent (figure 1c).

The pressure difference across a vent opening is potential energy. Assuming that viscous terms are negligible and that air is incompressible, this potential energy is converted into kinetic energy, and Bernoulli's equation applies.

$$1/2\ \rho\ V^2 = \Delta P \tag{15}$$

$$V = \sqrt{2\ \Delta P/\rho} \tag{16}$$

where

V = velocity of air entering or exiting the building, m/s
ΔP = the pressure difference, Pa
ρ = air density, kg/m^3

This velocity represents flow through an orifice. However, it is not applicable to infiltration through small cracks and pores in a building wall. Kreith and Eisenstadt, 1957, developed a power curve relationship

$$V = k\ \Delta P^n \tag{17}$$

where

k = porosity factor, $(m^3/s)/m^2\text{-}Pa^n$
n = flow exponent $(0.5 \leq n \leq 1.0)$

The flow exponent, n, equals 0.5 when the flow is completely turbulent. For laminar flow, the flow rate has a linear dependence on the pressure difference, and the flow exponent is one. For infiltration, flow is usually in transition and the exponent generally used is 0.65 (Sherman, 1980).

After calculating the velocity of the flow, the air flow is determined.

$$Q = cd \int_{area} V \, dA \tag{18}$$

where

Q = airflow, m^3/s
cd = coefficient of discharge (≤ 1.0) (for porous walls, $cd = 1.0$)
A = area of the opening, m^2

A typical value for the coefficient of discharge for a rectangular opening is 0.6. Bruce (1977) notes that this is probably low.

Assuming that the airflow in the building is steady, flow continuity applies; the net airflow is zero.

$$\sum_{j=1}^{N} cd_j \int_{area_j} \sqrt{2/\rho}\, \Delta P_j^{\;1/2} \, dA + \sum_{j=1}^{M} k_j \int_{area_j} \Delta P_j^{\;n} \, dA = 0 \tag{19}$$

where

N = number of vents or openings
M = number of porous surfaces

$$\Delta P_j = [\rho_o \, (V^{*2}/2) \, (cp_o - cp_i) + g(\rho_o - \rho_i)(\bar{h} - h)]$$

For known or assumed weather conditions and constant vent openings, the neutral pressure level, $\bar{h}$, the only unknown in this equation. Because the equation is not linear, $\bar{h}$ is determined by iteration. The ventilation rate can then be calculated.

IMPLEMENTING THE MODEL FOR CONTROL

The Controlled System

A natural ventilation system for a building is to be controlled by a microprocessor. The building is assumed to be instrumented to sense inside and outside air temperatures, incident solar insolation for each surface, and net wind pressure difference on each section. The microprocessor reads this information and adjusts vent openings according to a control program.

The program includes a data set describing the building that is being controlled. The parameters in the data set include the optimum inside temperature and permissible temperature hysteresis, the number of animal units and corresponding heat factors, and the heat from mechanical sources. The set also describes each surface of the building in terms of its dimensions; tilt angle relative to the horizontal; thermal properties of the surface (thermal transmittance, emittance, conductance and absorptance); and the number of openings. The openings could be cracks, slots, porous walls, ridge vents or wall vents. Information needed for each opening consists of the location and dimensions, the coefficient of discharge, the flow exponent (n in equation 17), and whether the vent is adjustable or not.

Control Strategy

The basic idea behind the control program is to compare the average inside temperature with the pre-determined optimum temperature. If the temperature is within the acceptable range, the microprocessor continues monitoring the sensors. If the inside temperature does not fall within the acceptable range, the program begins by reading the sensors and calculating a new ventilation rate based on the steady-state energy balance (equation 1). The revised ventilation rate is compared to the minimum acceptable air flow for controlling moisture and contamination levels in the building. The largest of the flows is taken as the new ventilation rate.

The program adjusts all positive (airflow into the building) vents as a unit and all negative (airflow out of the building) vents as a unit to achieve the required ventilation rate. Each separate vent adjustment is then modified to obtain achieve approximately equal airflows per meter length through the negative vents and the positive vents. This is based on the premise that equally distributed flows will promote complete air mixing in the building.

When the building reaches an acceptable average inside temperature, the control system continues to monitor the inside temperature. When the inside temperature is no longer within the specified range, the whole process begins again by reading the wind pressure difference, temperature, and solar sensors.

Computer Program

The computer program is written in pascal and was implemented on an IBM PC-XT using a turbo-pascal[1] compiler. The flow chart (figure 2) illustrates program logic. In the flow chart

$\bar{h}$ = neutral presure level, m
dif = increment for opening or closing vents and for adjusting $\bar{h}$, mm
t2 = time required for the air temperature in the building to stabilize, s
t1 = time allotted before verifying the inside air temperature after the vents have been adjusted (can assume t1 = 1/2 (t2)), s.

Due to the length of the computer program, it is not included in this paper. Program listings are available upon request from the senior author.

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[1]Trade names are mentioned only for completeness. No endorsement is implied.

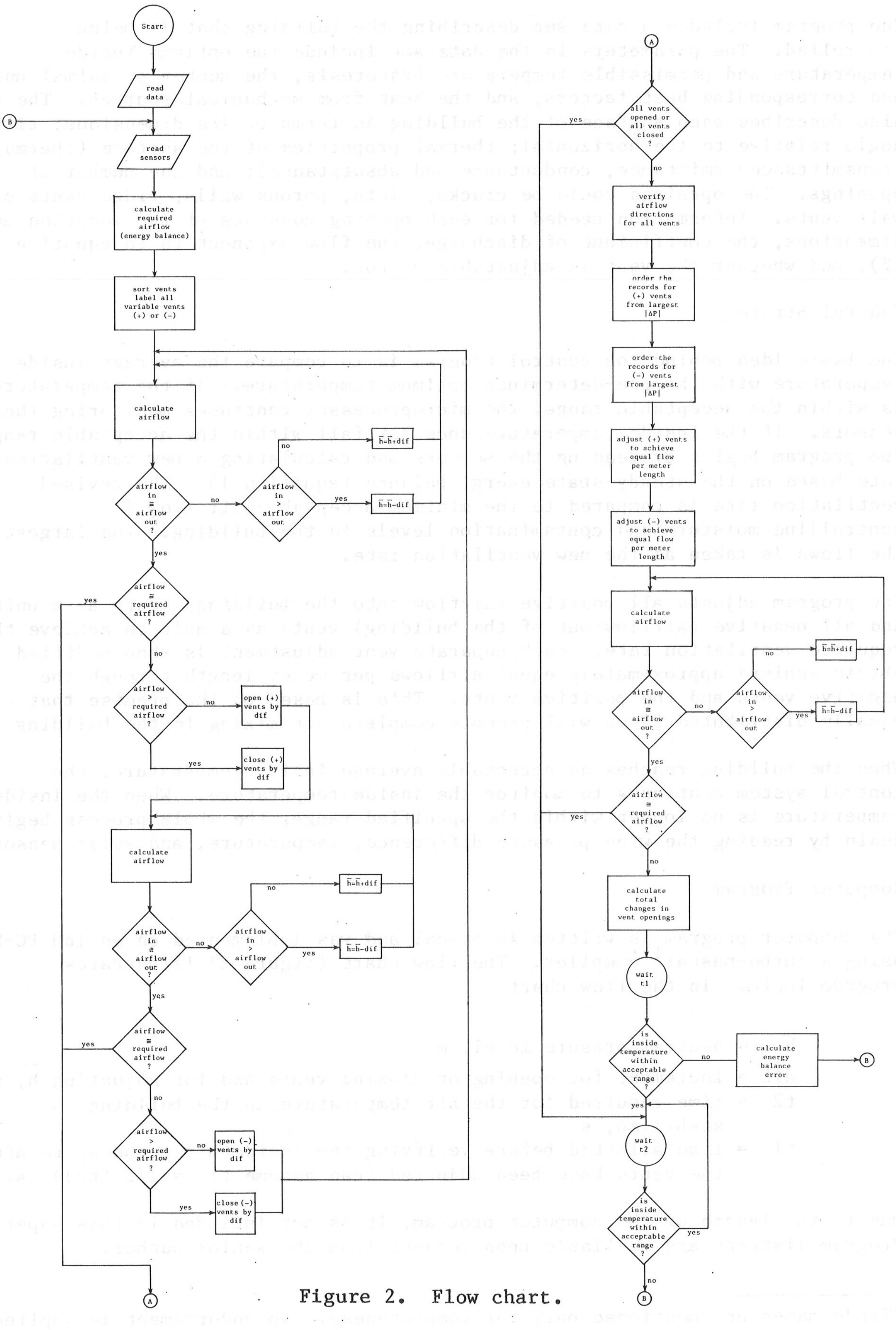

Figure 2. Flow chart.

Hardware Requirements to Implement Control

The proposed natural ventilation control system depends on accessing accurate weather data. Solar insolation and air temperatures are readily relayed to a microprocessor by photo cells and solid-state temperature sensors. A microprocessor could use wind velocity and wind pressure coefficients data to calculate wind pressure differences. However, wind pressure coefficients are not directly measurable. Instead, the microprocessor would directly measure wind pressure differences. An economical yet accurate instrumentation package with pressure transducers would have to be devised for measuring wind pressure differences.

EXAMPLE OF APPLICATION

Building Characteristics

A naturally ventilated dairy barn (figure 3) is 60m long, 12m wide, and 3m high at the eaves, with a roof slope of 4:12.

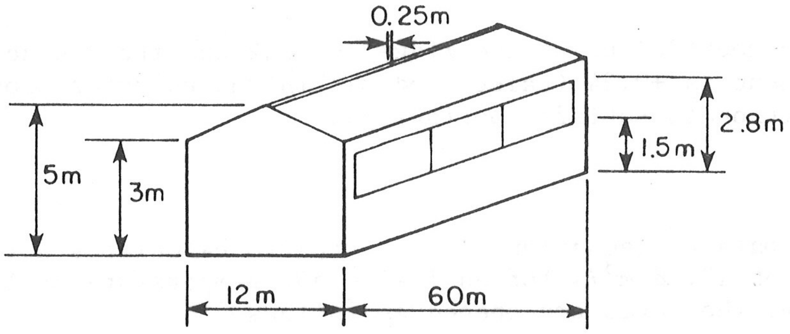

Figure 3. Building configuration.

There are three adjustable vents on each sidewall, each 19m long, and when totally open the vents are 1.3m wide, with the bottom of each vent 1.5 m from the ground. The ridge vent is 0.25m wide. (Infiltration is neglected in this simple example.) There are 80 cows inside the barn, and the optimal inside air temperature is 12.5 C. The U-value averaged for all walls and the roof is 1.0 W/m^2K and solar insolation on each surface is zero (night).

Weather

The outside air temperature is 6 C and the wind velocity is 2 m/s. The external wind pressure coefficients for the outside walls are shown in figure 4.

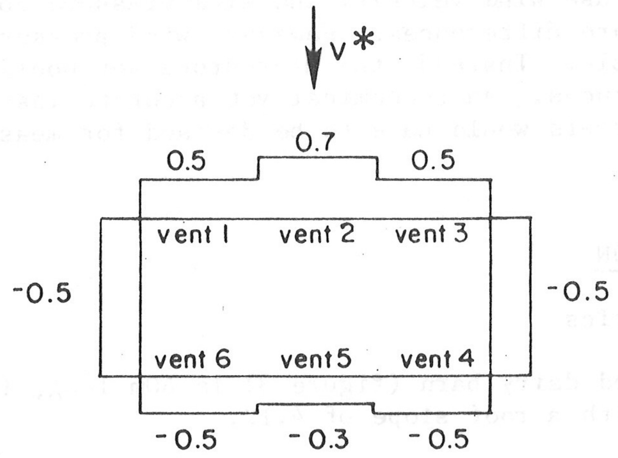

Figure 4. External wind pressure coefficients.

The wind pressure coefficient at the ridge is +0.2 and the inside wind pressure coefficient is +0.34 (calculated within the computer program, based on no heat production to satisfy continuity).

Results

Using the energy balance (equation 1), the program calculates a required ventilation rate of 13.28 m^3/s for an inside air temperature of 12.5 C. To achieve this flow, the vents are opened as follows:

Vent	Top of Vent Opening (m)	Vent Width (m)	Flow/m Length (m^2/s)
1	1.73	0.23	0.23
2	1.71	0.21	0.23
3	1.73	0.23	0.23
4	1.70	0.20	-0.13*
5	1.84	0.34	-0.13
6	1.70	0.20	-0.13

*(- indicates flow out of the building)

To illustrate control action, assume after the vents are adjusted, an inside air temperature of 10 C is read. A new required ventilation rate of 8.18 m^3/s is calculated. To achieve this flow, the vents are re-adjusted follows:

Vent	Top of Vent Opening (m)	Vent Width (m)	Flow/m Length (m^2/s)
1	1.64	0.14	0.14
2	1.62	0.12	0.14
3	1.64	0.14	0.14
4	1.63	0.13	-0.07
5	1.77	0.27	-0.07
6	1.63	0.13	-0.07

For this example, computer time for initializing and running the program was less than two minutes. Computer time for calculating the ventilation rate and adjusting vents the second time was less than 30 seconds.

SUMMARY

A control program for a natural ventilation system is described which calculates a required ventilation rate, then adjusts vent openings to achieve this ventilation rate with equally distributed flows. The control program calculates airflow through each opening using an algorithm that combines pressure differences caused by thermal buoyancy and wind forces.

A naturally-ventilated dairy barn example is presented to demonstrate the idea of equally distributed flows. The airflow per length of vent is equal for the three positive-flow vents and the three negative-flow vents. In the same example, a computer run time of under 30 seconds to make vent adjustments after the system is initialized shows the feasibility of using the program in a control system.

For further application, the computer program could be adapted to aid designers in placing and sizing vents in a building with natural ventilation.

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