Design and Management of Natural Ventilation Systems

John P. Chastain, Ph.D.

Department of Agricultural and Biological Engineering
Clemson University

2000

Introduction

Proper ventilation in needed to provide a healthy and productive environment for livestock and farm workers. A well-designed ventilation system provides an adequate amount of fresh air to supply oxygen, remove excess moisture, and control temperature. Exhaust mechanical ventilation systems use fans to generate a pressure difference across the walls of an animal building. Fresh air enters the building through well-distributed inlets and the stale moisture laden air exits through the fans. In contrast, natural ventilation uses local wind and temperature differences between the inside and outside of the building to move air through the structure. Fans are not used. Instead the quantity of airflow is determined by the size and placement of openings, roof slope, and orientation of the building with respect to prevailing wind direction. The pressure differences that drive the exchange of air are from the wind speed and the temperature difference between the inside and outside of the building. The pressure differences induced by a temperature difference is called the chimney effect.

The advantages of a natural ventilation system are: (1) reduced operating costs as compared to mechanical systems, (2) minimal concerns related to loss of ventilation due to power failure, and (3) reduced lighting costs during the day due to increased levels of natural light.

The disadvantages of natural ventilation are (1) poor control of temperature during cold weather, (2) reduced control of air distribution within the building, and (3) lack of effectiveness during summer conditions with minimal wind. Dairy cows do not require precise temperature control and can adapt to wide changes in temperature. As a result, natural ventilation is generally the preferred choice for dairy cow facilities.

The objective of this paper is to provide recommendations related to site selection, design, and management of natural ventilation systems.

Site Selection and Separation Distances

Selection of a suitable building site is a major factor in how well a naturally ventilated dairy barn will perform. Any compromises made related to site selection cannot be compensated for by inlet or side wall opening design. During periods of cold weather the chimney effect combined with properly sized eave and ridge vents can generally provide adequate air exchange. However, proper location of the building to take advantage of the wind is critically important for good summer ventilation.

Locate buildings on high ground if possible to minimize the effects of local obstructions such as trees and other buildings. Orient the building to take advantage of prevailing summer wind in all cases. Greater wind pressure differences are induced when the wind direction is perpendicular to the ridge and can result in an increase in ventilation due to suction on the ridge vent. In most parts of North America, naturally ventilated buildings should run east and west. Never orient a naturally ventilated building so as to run north and south because a significant portion of the shade provided by the roof of the building will fall of the housing area during part of the day.

Trees, silos, and other buildings can reduce natural ventilation from summer or winter wind. In general, an obstruction can disturb the airflow pattern at a distance of 5 to 10 times its height downwind. Locate naturally ventilated building at least 50 ft from upright silos and clusters of trees, and 75 ft away from all other buildings. Detailed separation distance recommendations are given in Table 1 for large buildings. If at all possible, locate the building such that no obstructions exist on the south side of the building.

Table 1. Recommended separation distances between naturally ventilated dairy barns based on the height and length of the upwind building (adapted from MWPS-33, 1989).

Height at	Length of Upwind Building (ft)						
Ridge (ft)	100	150	200	250	300	400	500
18	72	88	102	114	125	144	161
20	80	98	113	126	139	160	179
22	88	108	124	139	152	176	197
24	96	118	136	152	166	192	215
26	104	127	147	164	180	208	233
28	112	137	158	177	194	224	250
30	120	147	170	190	208	240	268
32	128	157	181	202	222	256	286

Building Characteristics and Openings

The ventilation rate in a naturally ventilated building depends on the wind speed, temperature difference between the interior and exterior, the size of the ventilation openings in the structure, and the distance in elevation between the openings. Since the wind speed and temperature differences can not be controlled the design and management of a natural ventilation system focuses on the placement and sizing of the openings. The primary types of openings used in a naturally ventilated dairy barn are eave, ridge, and wall openings, Figure 1. Wall openings can be located in the side wall and end wall. Controlling the size of these openings can control the ventilation rate to a great extent.

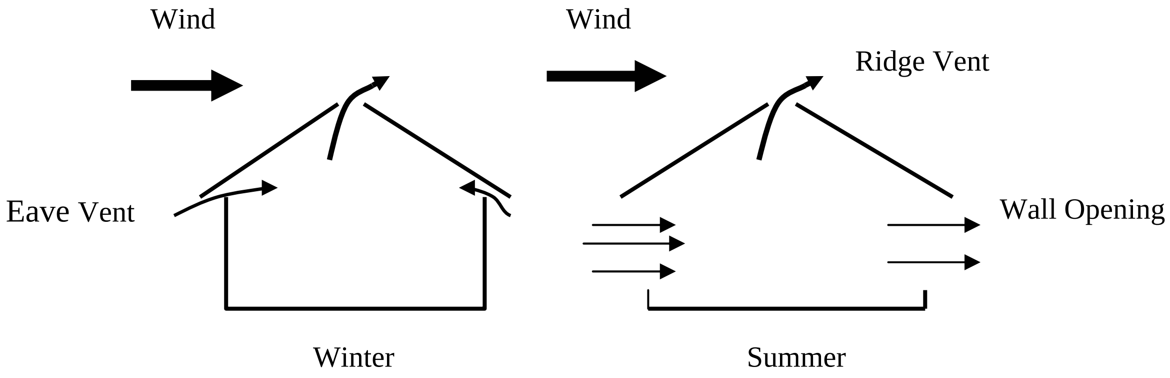

Figure 1. Typical openings used for natural ventilation of dairy buildings.

The amount of inlet control needed depends on the season of the year and the climate. For example, a dairy barn located in South Carolina or Florida may only use wall and ridge openings since winters are mild. However, a freestall dairy facility built in Minnesota or New York would require adjustable eave openings, wall openings, and a ridge vent. The amount of eave, or wall opening recommended will depend on the weather.

Sizing of Ridge and Eave Openings for Winter Ventilation

In cold and temperate regions adjustable eave and stationary ridge vents are needed to provide ventilation for moisture control and in some cases temperature modification. In parts of Canada, adjustable ridge vents have also been used.

Ridge Opening

The best ridge vent is a continuous stationary open ridge that runs the length of the entire building. The typical recommendation is to provide a minimum ridge opening of 6 inches for all dairy buildings up to 30 ft wide and 2 inches of open ridge for every 10 feet of building width for wider buildings (MWPS-7, 1995). For example, a 94 ft wide 4-row drive-through freestall barn would require a minimum of a 19 inch ridge opening.

Precipitation entering the building is not a significant problem with a properly sized ridge opening and proper animal density. The air leaving the building generally prevents a large portion of the rain or snow from entering the building. Building designs that avoid locating stalls or other critical areas under the ridge generally only require flashing or a small piece of ridge cap to protect the top of each truss or rafter.

If the small amount of precipitation that enters the ridge opening is objectionable it is better to protect areas below the ridge rather than build a cap. An internal gutter, shown in Figure 2, can be used to protect stalls or feeding areas if needed. The gutter is located 2 to 3 ft below the ridge opening and is sloped to channel rain water out of the building. An upstand that is

1.5 to 2 times as tall as the ridge opening is wide is another useful ridge treatment that will greatly reduce the amount of precipitation that enters the building without disrupting airflow.

Eave Openings

The winter ventilation rate can be controlled using adjustable eave openings in conjunction with a stationary, or nonadjustable, ridge opening. The eave openings should be constructed as continuous vents along each side of the building. Eave vents can be provided using the spaces between the trusses. Adjustable wall curtains that are closed by raising can be used to form an adjustable eave opening. Adjustable eave vents should be constructed so as to allow the vent to be opened to at least ½ of the ridge vent size (1 in per 10 ft of building width) to allow enough airflow during mild winter weather.

Roof Slope

The vertical separation between the eave and ridge openings has a significant impact on the pressure differences generated by the chimney effect (Chastain, 1987). Therefore, the roof slope is an important consideration in the design of a naturally ventilated building. Provide a roof with a 4/12 pitch to insure adequate separation distance between the eave and the ridge opening.

Management of Eave Openings During Winter

Adequate ventilation must be maintained during the winter to provide moisture removal and to control condensation. However, during extreme winter weather (below zero temperatures and high wind) the eave vents can be adjusted to reduce the airflow. The main goal of reducing the airflow is to provide daytime temperatures within the barn that are warm enough to allow the removal of frozen manure. Field experience, as well as ventilation and heat loss theory, indicates that it is impossible to have a warm naturally ventilated drive-through freestall barn and provide a healthy environment for dairy cows. The ventilation requirements for moisture control and the air volume within the barns are too great relative to the heat produced by the cows.

The purpose of this section is to provide additional guidelines for the management of natural ventilation systems during winter. The principles will be demonstrated using a four-row drive through freestall barn with freestalls arranged in a head-to-head orientation. The computed ventilation rates will be given in the units of cubic feet per minute per stall (cfm/stall). Results will be presented for periods of minimal wind, that is ventilation controlled by the chimney effect, and wind speeds up to 30 mph. The calculation procedures were based on information provided by Chastain (1987), Chastain and Colliver (1987) and Van Wicklen (1981).

Effect of Eave Opening Size on Winter Ventilation Rates During Periods of Minimal Wind

The lowest ventilation rates that can occur in winter are during periods of mild temperatures and minimal wind speed. In such a case, natural ventilation is driven by the chimney effect and depends on the temperature difference between the inside and outside of the building and the size of the eave openings. Ventilation rates were calculated for a freestall barn for eave openings ranging in size from 1 to 10 inches along each side of the building. The maximum eave opening was 10 inches since the ridge opening was set at 20 inches (about 2 in / 10 ft of building width). Also, the temperature of the air inside the freestall barn was varied from 3 to 10 degrees Fahrenheit above the outside temperature. The results are shown in Figure 2.

The results shown indicate that increasing the eave opening from 5 to 10 inches increases the ventilation rate by a factor of 1.6 regardless of the magnitude of the temperature difference. In addition, increasing the temperature difference from 3 to 10 degrees can almost double the ventilation rate. The recommended minimum winter ventilation rate for mechanically ventilated dairy barns is 50 cfm/cow to provide adequate moisture removal (MWPS-32, 1990). Therefore, these results indicate that using an eave vent less than 3 inches, or 0.3 inches per 10 ft of building width, during winter under conditions of minimal wind will result in an under ventilated barn. Furthermore, if the relative humidity is high then condensation and dripping is likely to occur and would yield an unhealthy environment for cows.

In most cases the minimum eave opening that should be used during mild winter weather would be 0.5 inches per 10 ft of building width (5 inches in Figure 2) to provide a ventilation rate of at least 100 cfm/stall. The extra airflow is needed to control condensation. However, if condensation is observed the opening should be increased to increase ventilation rate. In temperate regions of the United States, such as Kentucky and Tennessee, an eave opening of 1 inch per 10 ft of building width would be needed most of the time.

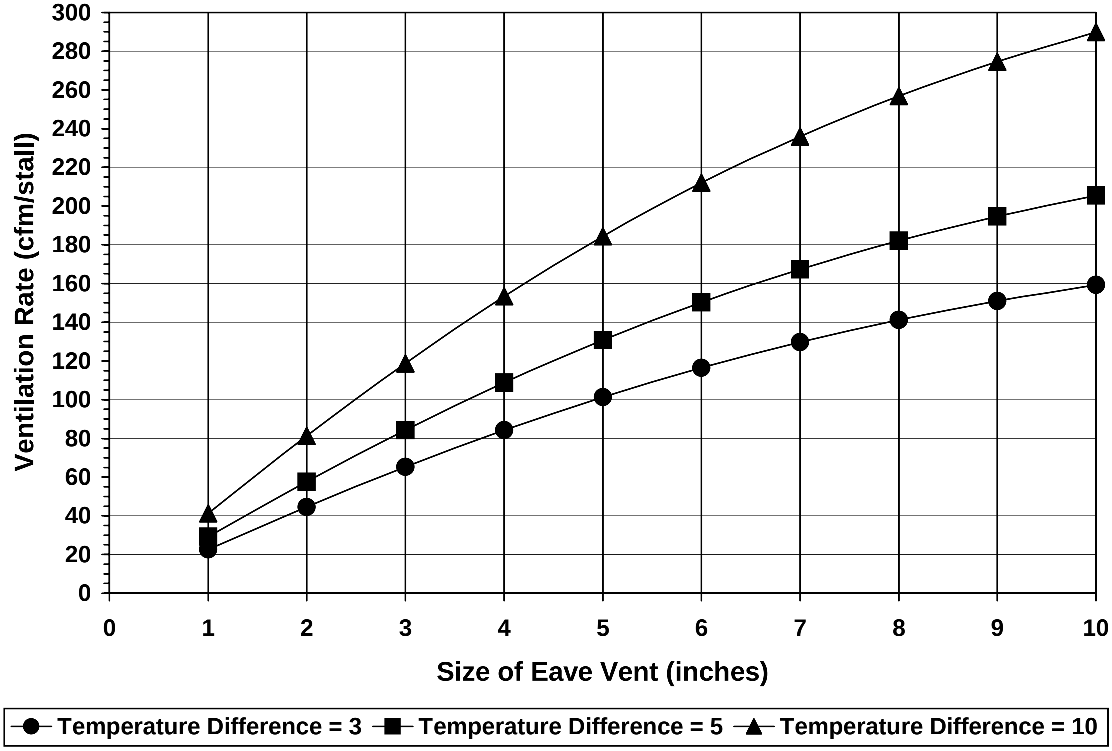

Figure 2. Effect of eave opening size on natural ventilation rate during winter under conditions of minimal wind (chimney effect). Ridge opening is 20 inches wide.

Effect of Eave Opening Size on Winter Ventilation Rates During Periods of Severe Winter Weather

High winds and cold temperatures characterize the most severe winter weather. Generally, such a combination can result in low temperature differences across the shell of the building and ventilation is controlled by the wind speed. The resulting ventilation rates for wind speeds ranging from 0 to 30 mph are given in Figure 3.

Using a minimum ventilation rate of 100 cfm/stall the minimum eave vents for a 4-row drive-through freestall barn during severe winter weather are: 5 inches for no wind, 3 inches for 2 mph wind, 2 inches for 5 mph wind, and 1 inch for 10 mph wind or more. Field experience in Minnesota during an extended period of –20 to –30 ° F temperatures and wind speeds of 10 mph or more indicated that an eave vent of 0.5 inches was adequate for a 4-row drive-through freestall barn.

Effect of Eave Opening and Insulation Value on Temperature Difference

The coldest period in a naturally ventilated freestall barn is at night when solar energy is not available to provide addition heating. The temperature difference between the inside and outside of the freestall barn was calculated using the ventilation rates given in Figure 2 and a heat production value of 1255 Btu/hr/cow. The results are shown in Figure 4.

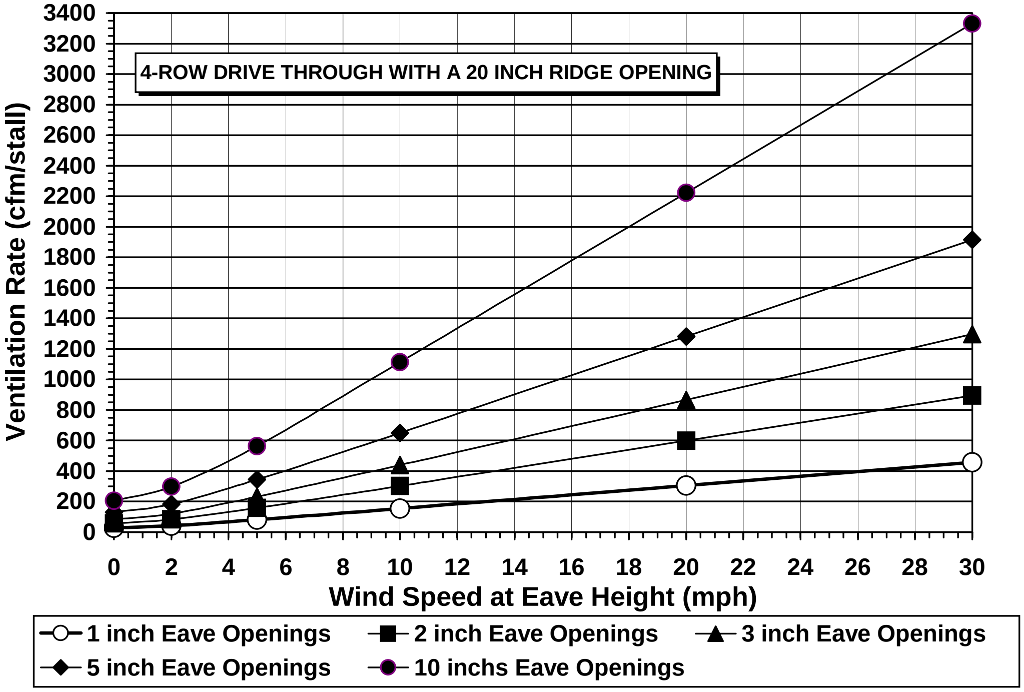

Figure 3. Effect of eave opening size on ventilation rate during severe winter weather.

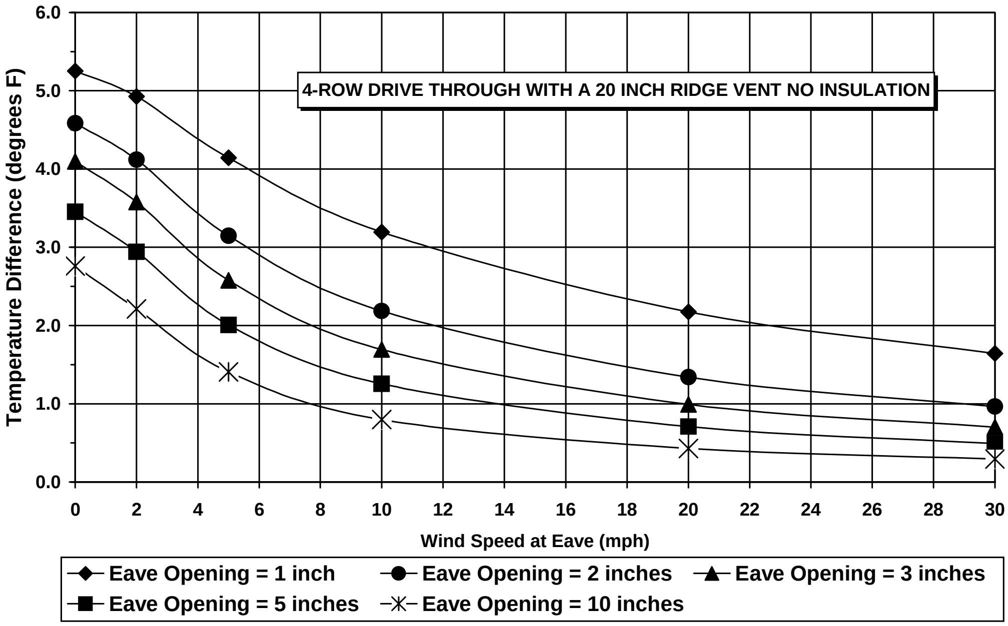

Figure 4. Nighttime inside-outside temperature differences during severe winter weather for a freestall barn.

The results indicate that for wind speeds less than 10 mph the nighttime inside temperature will be 1.5 to 4 degrees higher than the outside temperature if the eave openings are managed within the recommended range. During periods of high wind speed the inside temperature will only be about 2 degrees warmer than the outside temperature.

Adding insulation beneath the roof is often considered a viable method to increase the inside temperature of a naturally ventilated freestall barn during periods of extreme winter weather. The inside-outside temperature differences were calculated for an uninsulated roof (R = 0.85), a roof with insulation board (R = 7.85), and a roof with fiberglass insulation (R = 14.32) using the ventilation rates associated with a 10 mph wind (Figure 5). The results indicate that increasing the roof R-value from 0.85 to 7.85 only increased the temperature difference by 1.4 ° at an eave opening of 1 inch. An R-value of 14.32 only yielded a 1.6 ° increase in temperature difference. In order to achieve a higher temperature difference than shown the ventilation rate must be restricted to a level that is considered to be inadequate for moisture removal and condensation control. The only other alternative is to provide side and end walls with an R-value of 14.32. The results also indicate that at ventilation rates associated with 3 to 10 inch eave openings the effects of insulation are insignificant.

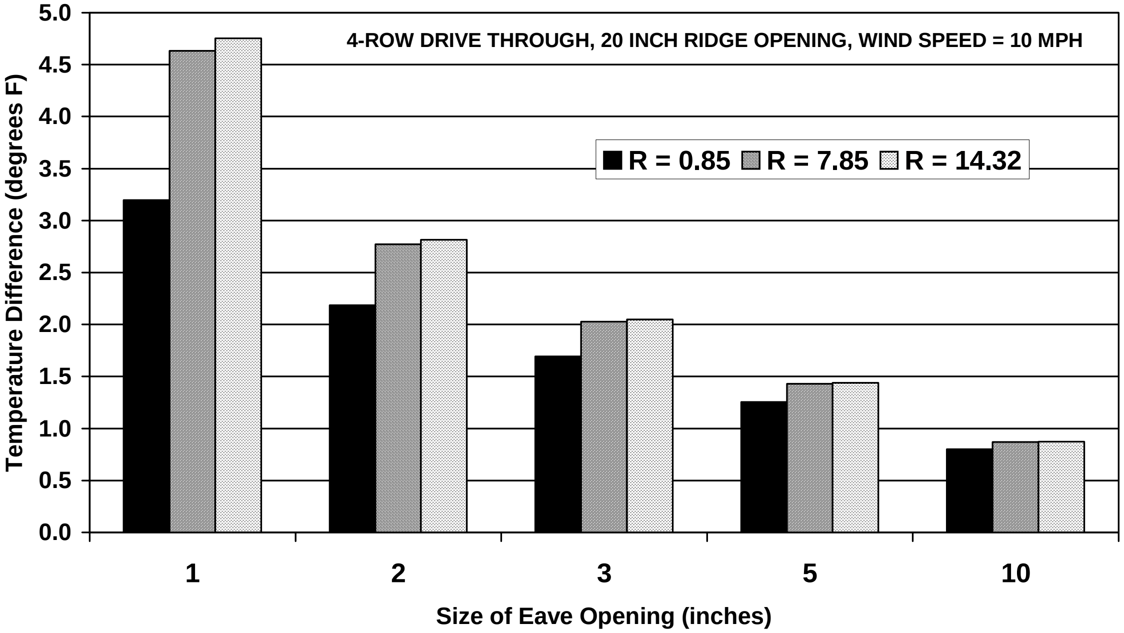

Figure 5. Effect of roof insulation R-value on inside-outside temperature differences during cold winter nights with a 10 mph wind.

In many cold climates, dairy producers that use uninsulated or minimally insulated barns with adjustable eave openings have found that the barn temperature will sufficiently increase during the day to allow frozen manure to be scraped from the alleys. This increase in temperature is due to the fact that outside temperatures are typically the highest during the middle of the day and solar radiation is also at a maximum. In fact, solar heating during the day can yield a greater increase in inside barn temperature than adding insulation to the roof as indicated in Figure 6.

The net solar heating value shown in Figure 6 represent the amount of solar energy that falls on the roof that is transferred to the barn interior. The values shown in the figure range from nighttime conditions (0 Btu/hr/sq. ft.) to 64 Btu/hr/sq. ft. and represents a sunny winter day. It was assumed that half of the energy that falls on the roof was available for heating the building, but did not include solar gain through the curtain wall or open ridge vent. Addition of a large amount of insulation to the roof and side walls would slow down the rate of solar heating and may reduce the daily rise in internal barn temperature.

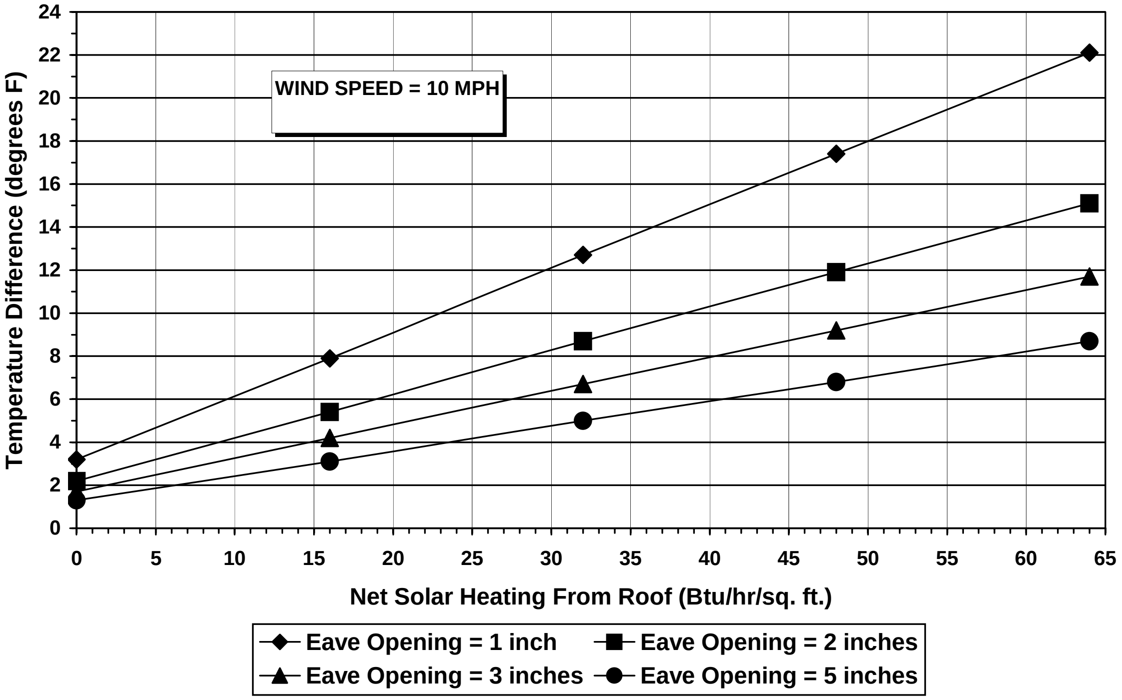

Figure 6. Effect of solar heating on inside-outside temperature differences for an uninsulated freestall barn in winter.

Dairy producers in cold climates have also resorted to increasing the stocking rate, that is cows per stall, in order to increase the barn temperature to facilitate removal of frozen manure. Increasing the stocking rate of a 4-row barn from 1.0 to 1.2 cows per stall provides almost the same increase in nighttime inside-outside temperature difference as adding insulation to the roof (Figure 7). The daytime barn temperatures would also be a few degrees higher due to the extra animal heat.

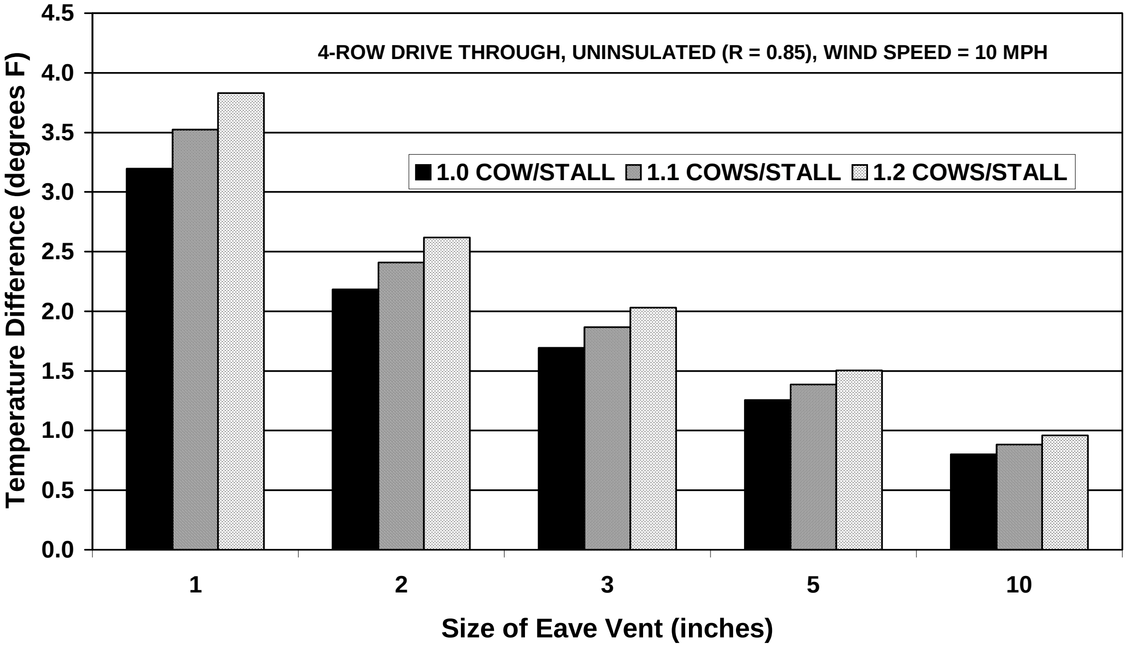

Figure 7. Effect of stocking rate on inside-outside temperature difference in a freestall barn during winter nighttime conditions.

Summary of Winter Eave Opening Management Recommendations

- In climates with mild winter temperatures a stationary eave opening of 1 inch per 10 ft of building width is sufficient.
- In areas where winter can be severe, adjustable eave openings are needed to allow the reduction of the ventilation rate during severe winter weather.
- During periods of minimal wind speed the minimum eave opening is 0.5 inches per 10 ft of building width to insure adequate airflow for moisture removal.
- Visible condensation during moderate to mild winter weather is a signal to increase airflow by increasing the eave opening.
- During periods of very cold temperatures and wind speeds of 10 mph or more the eave opening can be reduced to 1 inch for a 4-row drive-through freestall barn (0.10 inches per 10 ft of building width).
- During extreme winter weather the eave opening may need to be temporarily reduced to 0.5 inches (0.05 inches per 10 ft of building width).
- After the extreme winter weather has passed the eave opening must be restored to about 0.5 inches per 10 ft of building width. The eave opening should never be closed completely.
- Adding roof insulation is not a very effective method of increasing the interior barn temperature unless the barn is under-ventilated. Therefore roof insulation cannot be recommended except in the most severe climates.

- Solar heating during the middle of the day combined with a restricted eave opening results in a better increase in barn temperature than adding insulation and facilitates removal of manure during severe winter conditions.
- Increasing the stocking rate is about as effective as adding roof insulation.

Openings for Summer Ventilation

As shown in Figure 1, the types of openings used during summer are ridge and wall openings. The basic rules for summer natural ventilation are: maximize wall opening area while providing adequate shade from the sun. The most cost-effective method of providing large wall openings is to use curtain walls. The curtain design should allow the curtain to be rolled up and fastened securely to maximize the effective opening area and to minimize damage by wind and rodents to the curtain.

Effect of Wall Opening on Summer Ventilation Rate

Increasing the effective wall opening area greatly enhances summer ventilation as indicated in Figure 8.

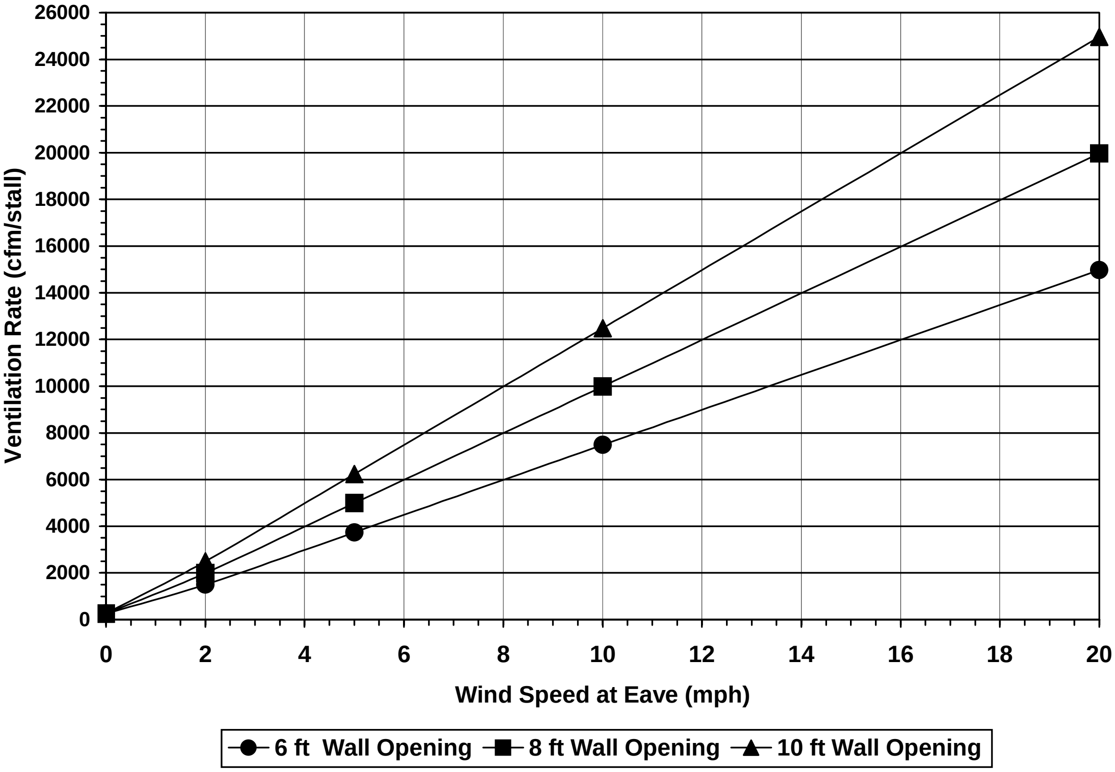

Figure 8. Effect of wall opening size on summer natural ventilation rate for a 4-row, drive-through freestall barn (ridge opening = 2 inches / 10 ft of building width).

Mechanically ventilated dairy barns are typically designed to provide 500 to 600 cfm/cow (MWPS-32, 1990). Therefore, the results given in the figure indicate that natural ventilation with only a 2 mph wind can provide more airflow than a mechanical ventilation system.

In recent years, the trend has been to increase the side wall height in order to increase the wall opening area. However, as the side wall height increases the amount of solar energy that reaches the freestall area also increases and can be counter productive in warm climates. Proper site selection and separation distances combined with wall curtain designs that achieve the maximum possible effective wall opening area should be emphasized over side wall height. The minimum side wall height that should be considered for a naturally ventilated dairy barn is 10 ft. With a well designed wall curtain the effective wall opening can be 7 to 8 ft. Increasing the side wall height to 12 ft can yield a wall opening of 9 to 10 ft. Side wall heights greater than 12 ft are rarely needed. However, the maximum wall height that should be considered is 14 ft.

Effect of Ridge Opening on Summer Ventilation

Some freestall barn designs provide a solid insulated ceiling without a ridge opening and side wall curtains. This concept was developed for use in areas with consistent wind speeds. However, the lack of a ridge opening reduces the summer ventilation rate as shown in Figure 9. When the wind blows in a direction that is perpendicular to a ridge opening additional airflow is induced. Also, increasing the size of the ridge opening from 2 to 3 inches per 10 ft of building width had a negligible effect on the summer ventilation rate due to wind.

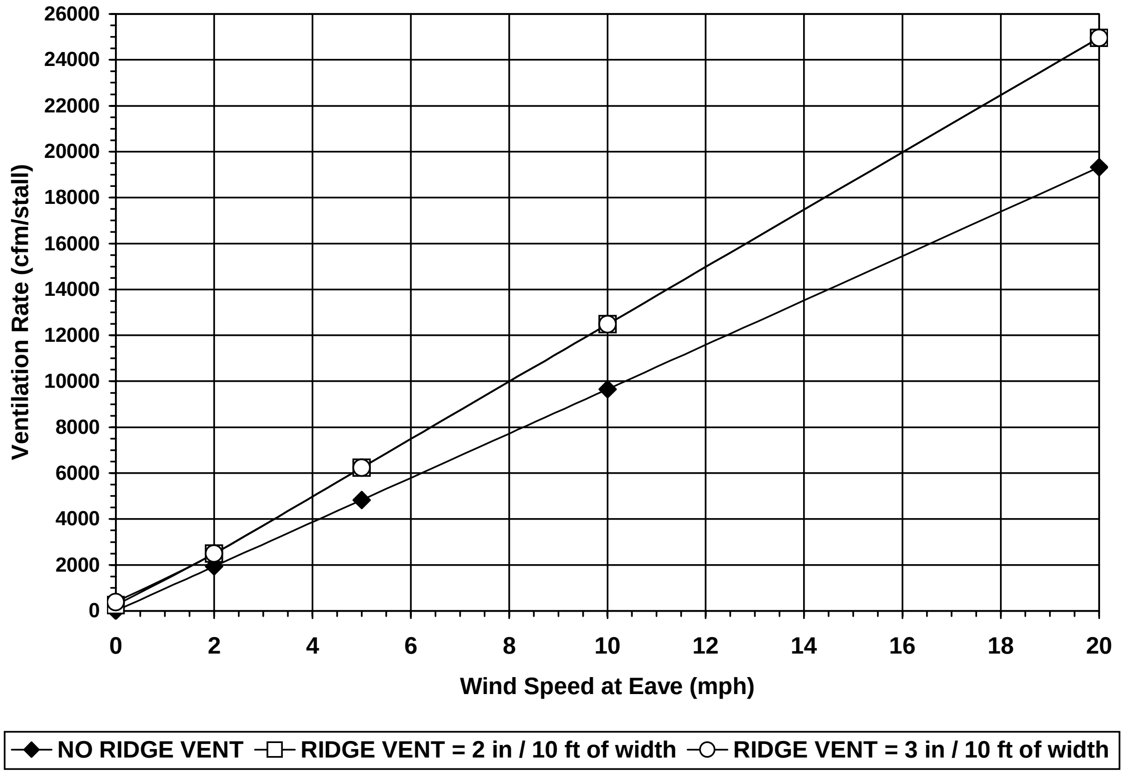

Figure 9. Effect of ridge opening size on summer ventilation controlled by wind (side wall opening = 10 ft).

In many parts of the Southeastern United States the hottest summer temperatures are often associated with minimal wind. In this situation the chimney effect plays the dominant role in natural ventilation. The influence of the ridge opening size on the ventilation rate during conditions of minimal wind is shown in Figure 10.

The results indicate that the ventilation rate is increased by 50% for every additional inch of ridge opening that is provided per 10 ft of building width. Therefore, doubling the size of the ridge opening can double the ventilation rate due to the chimney effect. However, if the ridge opening is too large the amount of solar heating of the animals and the feed will increase. Increasing the ridge opening from 2 to 3 or 4 inches per 10 ft of building width may be beneficial for dairy herds located in South Carolina, Georgia, Florida, and other warm, humid climates.

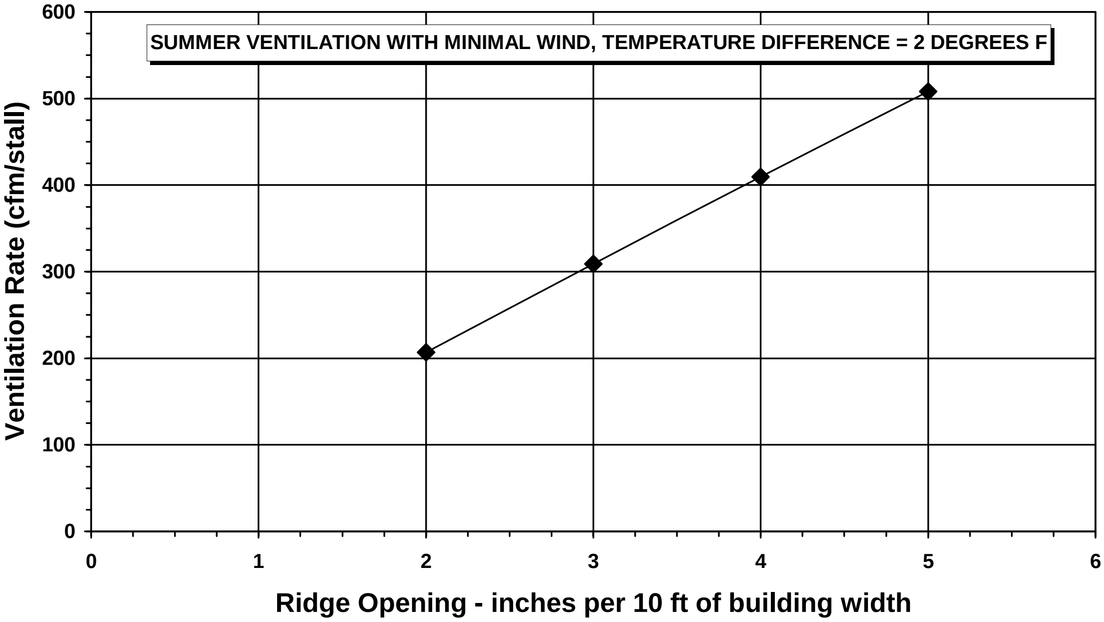

Figure 10. Effect of ridge opening size on summer natural ventilation rates for a 4-row drive-through freestall barn.

Comparison of 4-Row and 6-Row Barns

Six-row freestall barns are often considered by dairy producers since less building space must be built per stall. Many 4-row drive through freestall barns provide 100 to 110 ft^2/stall while most 6-row barns only provide 76 ft^2/stall. The lower square footage per stall increases the amount of animal heat generated in the barn and has the same effect on the barn temperature as an increase in stocking rate. Increasing the amount of animal heat can increase the internal barn temperature during severe winter as indicated previously. However, the summer ventilation in a 6-row barn is significantly compromised as indicated in Figure 11. The ventilation rate (cfm/stall) for a 6-row barn is 37% lower than for a 4-row barn.

Therefore, a 6-row barn cannot be recommended for warm or temperate climates. However, it may provide a viable alternative in cold climates.

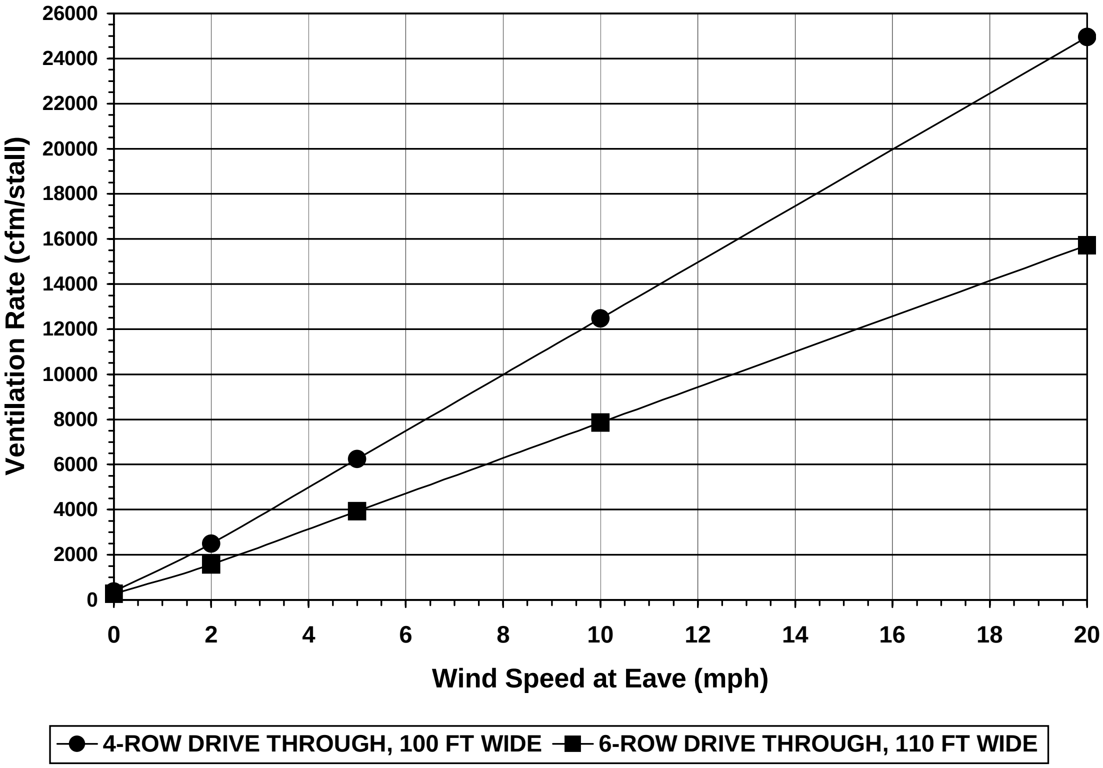

Figure 11. Comparison of summer ventilation rates for 4 and 6 row freestall barns.

Summary

The fundamental principles related to the design and management of natural ventilation systems for dairy cow housing was demonstrated using a 4-row drive through freestall barn as an example. Recommendations for the sizing of ridge, eave, and wall openings were developed based on calculated ventilation rates due to the wind and chimney effect for winter and summer conditions. The effect of roof insulation, stocking rate, and solar heating on the internal barn temperature during winter was also presented.

It was determined that solar heating is a more important factor in managing frozen manure in cold climates than providing roof insulation. Stocking rates of 1.1 to 1.2 provided a small increase in the nighttime internal barn temperatures. Ventilation rates were also calculated for a 6-row freestall barn and compared to the results for the 4-row barn. The results indicate that the summer ventilation rate for a 6-row barn was 37% less than for the 4-row barn (stocking rate = 1.0). It was concluded that the 6-row barn is not a suitable alternative for temperate or hot climates, but may be a viable alternative for cold climates.

References

Chastain, J.P., D.G. Colliver, and P.W. Winner. 1987. Computation of discharge coefficients for laminar flow in rectangular and cylindrical openings. ASHRAE Transactions 93(2B):2259-2283.

Chastain, J.P. 1987. Pressure gradients and the location of the neutral pressure axis for low-rise structures under pure stack conditions. Unpublished MS thesis, Department of Agricultural Engineering, University of Kentucky, Lexington KY.

MWPS-7. 1995. *Dairy Freestall Housing and Equipment* . 5th edition, Midwest Plan Service, Agricultural and Biosystems Engineering Department, Iowa State University, 122 Davidson Hall, Ames IA 50011-3080.

MWPS-33. 1989. *Natural Ventilating Systems for Livestock Housing*. 1st edition, Midwest Plan Service, Agricultural and Biosystems Engineering Department, Iowa State University, 122 Davidson Hall, Ames IA 50011-3080.

MWPS-32. 1990. *Mechanical Ventilating Systems for Livestock Housing*. 1st edition, Midwest Plan Service, Agricultural and Biosystems Engineering Department, Iowa State University, 122 Davidson Hall, Ames IA 50011-3080.

Van Wicklen, G. 1982. Management of Structural Environments. Class notes on calculation of wind induced natural ventilation using pressure coefficients. University of Georgia, Department of Biological and Agricultural Engineering, Driftmeyer Engineering Center, Athens, GA.