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Abstract

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Keywords
Natural Ventilation, Control, Indoor Climate

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AUTOMATED CONTROL LOGIC FOR NATURALLY VENTILATED AGRICULTURAL STRUCTURES

S. J. Hoff

ABSTRACT. *An innovative control strategy for a naturally ventilated (NV) swine finishing building was evaluated. Extensive monitoring of an existing NV-controlled swine finishing building indicated that the building temperature control was ±3°C of set-point for less than 50% of the time, with 20% of the time greater than ±6°C. Based on the experience gained from this monitoring, the building was modified to accommodate testing and development of a new NV control logic. Using the improved NV control logic, the building temperature was ±2°C of the set-point for 91% of the time, and, ±3°C for 97% of the time for a wide range of cold and mild weather conditions with no supplemental heater use. A routine using inside relative humidity feedback was used to preserve indoor air quality levels through a series of purging routines.*

Keywords. *Natural Ventilation, Control, Indoor Climate*

Naturally ventilated livestock and poultry facilities have been used for many years. One of the earliest documented NV-controlled (NV) designs was for a horse stable (Hales, 1758) where an elaborate system of fresh-air intakes near the floor of the stable combined with a manually adjusted ridge vent provided the necessary indoor climate control. Many advancements have been made but the general techniques have remained the same. Today's livestock and poultry production systems require better control of the thermal environment for animals to reach their genetic potential in growth and feed efficiency. For NV to be economically viable and meet environmental control requirements for efficient livestock and poultry production, system performance must improve. With production costs rising and profit margins declining, NV is an attractive option for maintaining the indoor climate at desired levels, provided that efficient control strategies exist.

Zhang et al. (1989) developed a comprehensive model describing the mathematics of thermal buoyancy and wind effects on the NV process and demonstrated its effectiveness with a field study. Van't Klooster (1996) developed a control algorithm for NV buildings using animal growth curves and a heat balance model to determine required climate control levels. Zhou et al. (1997) used a computer model to compare predicted and measured ventilation rates with two well-instrumented NV barns and found good agreement between the actual and predicted ventilation rates. Ventilation rates were measured using a carbon dioxide balance approach. Ventilation rates were estimated using a series of predefined opening effectiveness levels (Choinere et al., 1992). The method showed that a computer control system could use outside climate conditions to control for desired ventilation rates. Naas et al. (1998) conducted wind tunnel tests to determine opening effectiveness levels for NV buildings. A series of opening effectiveness levels could be used to estimate the ventilation rate in NV buildings as affected by wind speed and direction.

The objectives of this research project were to: 1) evaluate NV control performance by monitoring a commercial NV-controlled swine finishing building, and 2) develop and test a new control method for NV barns using this same swine finishing building.

EVALUATION OF A NV-CONTROLLED SWINE FINISHING FACILITY: OBJECTIVE ONE

The purpose of objective one was to monitor the performance of an NV swine finishing building to evaluate the successes and failures of the NV control logic used for this building. To accomplish this objective, a swine finishing building in central Iowa was monitored for 1.5 years. Late winter and early spring control performance was summarized.

BUILDING MONITORED

The building monitored was a swine finishing building (fig. 1) designed to house 550 pigs between 55 and 115 kg. The building used a shallow-pit pull-plug manure handling system and was oriented with the ridge line along an east-west axis. Table 1 summarizes the size and thermal characteristics for this building. This building was instrumented with 25 T-type thermocouples positioned in the building's center-plane along with a single capacitive-plate relative humidity sensor (Model HX92; Omega, Inc., Stamford, Conn). The sensing grid is shown in figure 1. A data logger (Model CR-10/AM416; Campbell Scientific, Inc., Logan, Utah) was used to collect and store all sensor data. Data was collected on a 1-min sampling interval with the 15-min average stored for later analysis. An on-site

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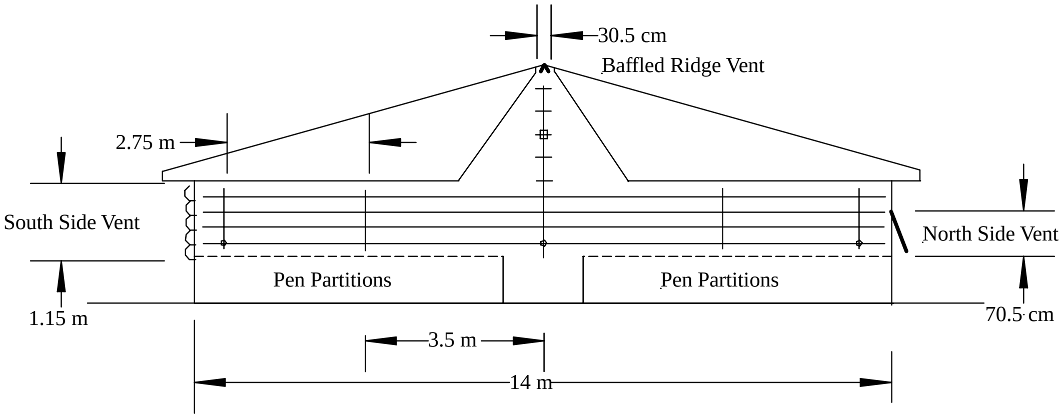


Figure 1. Side-view of building monitored. The internal crossing-points represent temperature monitoring locations. Boxed location represents relative humidity monitoring location. The three circled locations represent the near-animal level (NAL) temperatures used for analysis.

weather station (Campbell Scientific, Inc., Logan, Utah) located at a 10-m height was used to record outside temperature, wind speed, wind direction, and relative humidity.

The interior roof line consisted of an inverted-V. Except for the center 2.4 m, the ceiling was flat and well insulated (4.4 m^2-°C/W) from the attic space. At the center 2.4 m, the interior roof sloped upwards towards the ridge vent opening. This section of the roof line was also well insulated (4.4 m^2-°C/W).

Ventilation Strategy

The monitored building was ventilated completely by NV. No supplemental heat was used. The south-side (SS) vent was 1.15 m wide along the entire 29 m building length and used a single layer non-insulated curtain for controlling the opening size. This curtain was thermostatically controlled, with the thermostat located directly on the east wall in the center of the southern half of the building. This end wall was adjacent to an attached heated room. The north-side (NS) vent openings consisted of 21 70.5-cm wide, manually adjusted hinged insulated doors, hinged at the top. These doors were each 1.2 m long and were installed uniformly along the 29-m building length. The ridge vent was a continuous 30.5-cm wide manually adjusted opening with inside hinged baffles to control the opening size. These baffles were hinged at the center and folded up together to adjust the ridge opening size to provide opening control.

The operator of this building would close the NS doors during the winter months, except for an approximate 1-cm gap at the bottom closure. The ridge vent was manually adjusted periodically throughout the day, and especially at the end of the day according to the projected nighttime conditions. If the forecast was for cold windy conditions, the ridge vent was completely shut. The SS curtain was allowed to operate automatically with the feedback thermostat installed. During periods of extreme cold, the motor controlling limit switch was set to prevent the curtain from opening beyond 30 cm.

This building was a modified environment, NV-controlled building (MWPS, 2001) and represents a large class of NV-controlled buildings in operation. In modified environment NV control, the desire is to keep the building environment within a reasonable range (±3°C) around the desired set-point temperature. Typically, modified environment NV-controlled buildings have manually adjusted vent openings and many do not use supplemental heat, as was the case for the monitored building. This building, located at the Iowa State University Swine Nutrition and Management Research Center, was designed to conduct controlled feeding trials for finishing pigs.

Table 1. Size and thermal characteristics of the building monitored.

Building Component	Size	R-Value (m^2 C/W)	
		Before	After
Width	14 m		
Length	29 m		
Eave height	2.4 m		
Ridge height	4.7 m		
NS opening[a]	70.5 cm	1.94	1.19
SS opening[a]	1.15 m	0.18	0.28
Ridge opening	30.5 cm		
Sidewalls[b]	1.3 m	2.64	
End-walls		3.52	
Attic/roof system		4.40	

[a] R-Value for north side (NS) hinged doors (before renovation), NS curtain (after renovation), and south side (SS) curtain.

[b] R-Value corresponds to solid portion of sidewall which includes 30 cm above the curtain opening and 95 cm of concrete from the floor to the bottom of the curtain opening.

Results and Discussion: Objective One

Temperature Control Characteristics

Figure 2 summarizes a continuous 15-day near animal-level (NAL) temperature profile used for analysis. This period was selected because it represented a wide fluctuation in outdoor climates typical of winter-to-spring control periods. The profile shown in figure 2 represents the average temperature 1.2 m above the floor (i.e., NAL) across the width of the building. The building set-point temperature during this period was 16°C.

The average temperature maintained in the building during this 15-day period was 13.1°C with a standard deviation of 3.8°C. The maximum 15-min average inside NAL temperature measured was 20.8°C with a minimum of 1.4°C. During this same period, the outside temperature ranged from a maximum of 9.6°C to a minimum of -17.7°C.

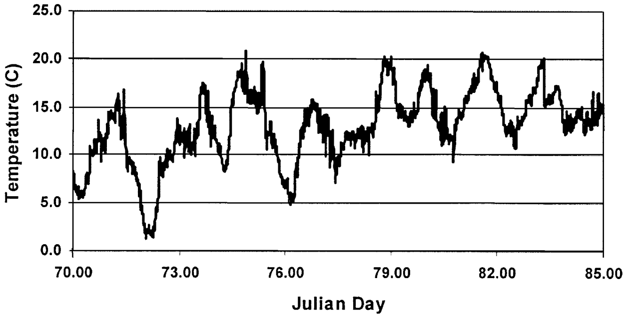
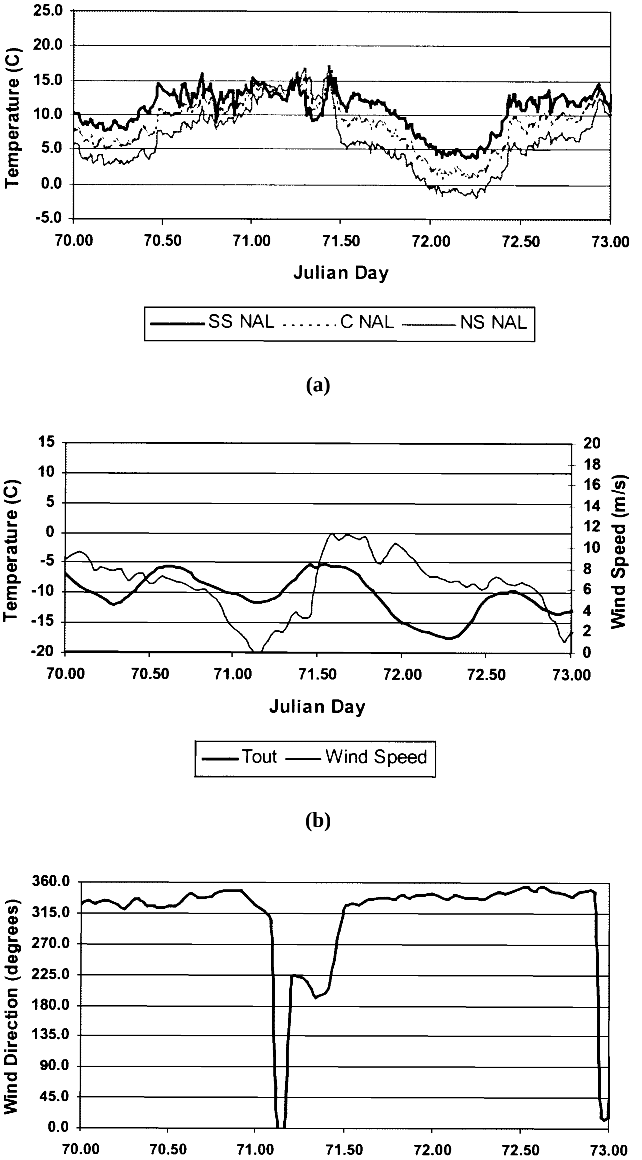


Figure 2. Average NAL temperature for a 15-day period in March (JD70 to JD85). Set-point temperature during this time was 16°C.



(a)

(b)

(c)

Figure 3. Close-up view of Julian Days 70-73 showing (a) near animal level (NAL) temperatures at the south (SS), center (C), and north (NS) regions of the barn, (b) outside temperature and wind speed, and (c) wind direction.

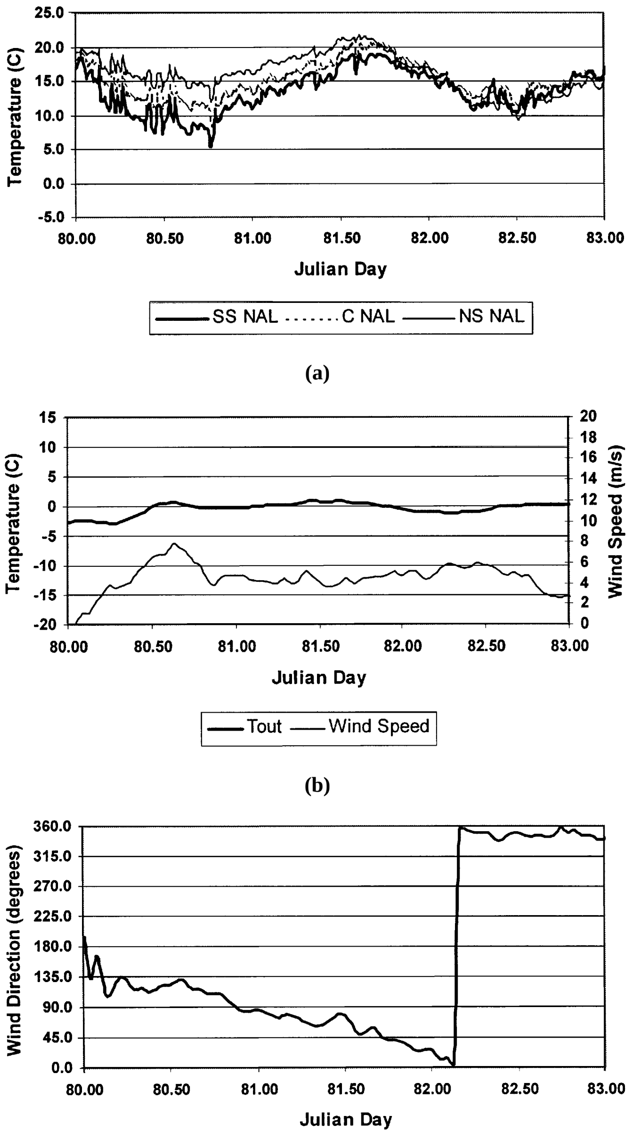
Further analysis of this data set indicated that the measured temperature was maintained at ±1°C, ±2°C, ±3°C, ±4°C, ±5°C, and ±6°C of the set-point temperature for 16%, 33%, 50%, 66%, 77%, and 82% of the time, respectively. This control performance implies that the absolute error between average NAL temperature and the desired set-point was greater than 6°C for 18% of the time.

Two representative three-day periods were used for further analysis of the NV control characteristics. Figure 3 presents the three NAL temperatures shown in figure 1 for Julian Days (JD) 70 through 72 and figure 4 represents the same three NAL temperatures for JD's 80 through 82. These three locations represent temperatures near the SS curtain, center of the building, and near the NS hinged doors. These two distinct periods were chosen for further analysis because of the shifting wind directions during these periods.

The NAL temperatures shown in figure 3a indicates that for most of this three-day period, the NS of the building remained on average 5°C below the SS of the barn. During most of this period, the wind was predominantly from the north (0 or 360 degrees represents wind from due north, 90 degrees implies wind from due east), except the period between JD 71.25 and 71.50, when the wind shifted, originating from the south. The result of this shifting wind pattern is shown in Figure 3a with a complete reversal of the NAL temperature profile. During this same shifting wind pattern, the wind speed rose significantly from near zero at JD 71.20 to 11.5 m/s at JD 71.60.

This trend in NAL temperatures can be explained by the ventilating method during this period. For this building, the only automatically controlled element was the SS curtain. The NS hinged doors remained closed, except for an approximate 1.0-cm crack at the bottom opening of the door. During periods with predominant northerly winds, infiltration air entered this small opening, causing significant temperature fluctuations at the three NAL locations. When the wind shifted to a southerly origin, the north and south-side NAL temperatures equilibrated. In addition, the thermostat used to control the SS curtain was located in the south-east region of the building, attached to the end wall. The lower than desired NS NAL temperature was never sensed by the thermostat.

The NAL temperatures shown in figure 4a represent another interesting control period. For this three-day period (JD 80 to 82), the wind originated predominantly from the south to south-east for JD 80 to 81 and then shifted to a northerly origin thereafter. For those initial periods with a southerly wind, the SS NAL temperature was between 5 and 8°C below the NS NAL temperature, which represents a complete reversal from the previous period analyzed. As winds shifted to a northerly origin, the NAL temperatures tended to equilibrate, a result of the closed NS doors, moderate outside temperature (0°C), and relatively low wind speed (3 to 5 m/s). Unlike the first period analyzed, a shifting wind pattern with a northerly origin did not cause the NS NAL temperature to fall below the rest of the building. The moderate outside temperature combined with low wind speeds did not contribute significantly to infiltration air that would have otherwise entered through the NS door.



(a)

(b)

(c)

Figure 4. Close-up view of Julian Days 80-83 showing (a) near animal level (NAL) temperatures at the south, center, and north regions of the barn, (b) outside temperature and wind speed, and (c) wind direction.

SUMMARY: OBJECTIVE ONE

The NV building monitored was controlled like many NV buildings used today for production agriculture. Combinations of automated and manual vent control, along with a single feedback temperature sensor, are common. The control capabilities shown in figures 2 to 4 would be typical for most cold-climate NV barns using this strategy.

At the conclusion of this monitoring effort, several areas of improvement in NV control were identified. Clearly, manual vent control of any kind should not be used if the desire is to have control of the production environment. In addition, the single feedback sensor used was not adequate to properly characterize the building's interior climate changes as affected by changing weather conditions. Better control of both north- and south-side vents, along with multiple and proper sensor placement, would be expected to better represent the average NAL climate in the north- and south-side zones. The plots shown in figures 3 and 4 clearly show how a properly placed feedback sensor in the building could be used to assess the predominant wind direction. A temperature sensor placed strategically near both the north and south sides of the building could be used to assess wind direction and appropriately control the corresponding vent.

The monitoring results from objective one indicated several key areas for improving environmental control features for cold-climate NV buildings:

- Manual control of vents. Should be entirely avoided if your desire is to maintain good thermal control of the production environment. Weather patterns change too quickly and frequently to allow for manual control.
- Independent control of NV vents. Due to the variability in weather patterns, having the ability to automatically control all vents independently is important.
- Sensor placement. Feedback sensors must be placed in the building to both represent the NAL and to quickly sense changes in weather patterns. This is critical if large variations in NAL temperatures are to be avoided.
- Coordinate vent activity. With independent control of vents, it is extremely important to coordinate the open/close activity of vents to minimize short-circuiting and ridge-vent down drafting. For example, if an NV barn is allowed to ventilate with just one vent, short-circuiting through this vent will occur, sacrificing proper fresh-air distribution. Airflow pattern control is critical to properly distribute cold-weather minimum ventilation air.

DEVELOPMENT AND TESTING OF NV CONTROL STRATEGIES: OBJECTIVE TWO

The results from objective one indicated several key areas for improving the environmental control features of NV barns. To accomplish objective two, the building monitored for objective one was physically modified to develop an improved NV control logic. The building was modified, as shown in figure 5, in the following ways:

- The NS insulated doors were replaced with a seven-layer fiber-filled curtain, opening from top to bottom and fitted with a cabling system and actuator. This curtain, at full closure, was set up to allow for a 2.5-cm overlap to prevent excessive curtain leakage (Hoff, 2001). This change allowed for easier and automated NS vent opening control and better control of infiltration air.
- The SS single-layer curtain was replaced with a two-layer curtain, opening from top to bottom. Again, this curtain was set up so that a 2.5-cm overlap existed at full closure to minimize infiltration air from entering the building.
- The ridge vent manual winch adjustment system was replaced with an automated linear actuator.
- The building was configured as a two-zone controlled system, split into north and south sides of the building. Three temperature feedback sensors (AD592; Analog Devices, Inc., Norwood, Mass.) were placed in both the north and south half zones, 3 m from the curtain and 1.2 m from the floor, as shown in figure 5.
- A single relative humidity feedback sensor (Model HX92; Omega, Inc., Stamford, Conn.) was installed in the barn, placed 2.4 m from the floor at the center of the barn and offset 1 m to the north of the ridge-line axis.

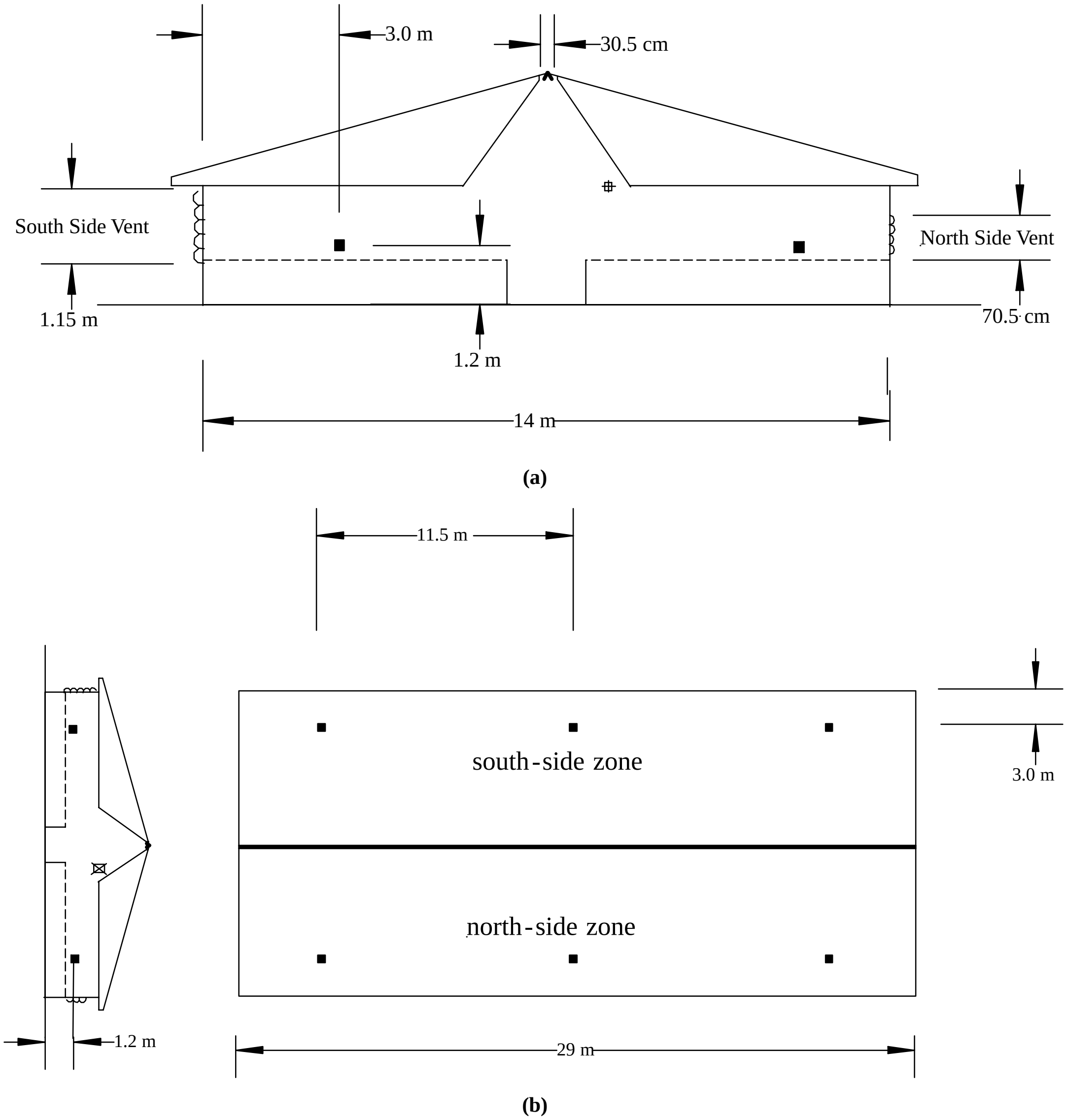


Figure 5. Modifications made to the building to provide independent and automated vent control. (a) NS curtain, SS curtain, and RV provided with automated actuation; NS hinged doors replaced with an insulated curtain. (b) Building volume separated into two control zones; north and south, with each described by the average of three temperature feedback sensors at the locations shown. Cross-hatched box location represents the relative humidity sensor location used for cold weather air quality control.

These five changes allowed the control system to sense NAL temperature as well as the average relative humidity within the building. In addition, each of the vents (north curtain, south curtain, ridge) were capable of being adjusted independently of the others with the actuators installed. The north- and south-side vents were controlled using the temperature sensors located in the north- and south-side zones, respectively. The ridge vent was controlled proportionally by the average temperature in the entire building, the current relative humidity conditions within the building, and most importantly by the status of sidewall curtain opening levels.

NV CONTROL LOGIC DEVELOPED

The key elements to the NV controller developed were that all vent openings could be independently controlled, with their individual control decisions based upon sensors located close to the animals in the region most affected by each of the vents. For example, if a sudden change in weather conditions resulted in a southerly wind, then the SS temperature sensors will detect this change quickly allowing the SS vent to be adjusted quickly. In this manner, no knowledge of actual outside weather conditions is required; instead, the control system could respond quickly to outside weather conditions that affect the internal climate. The advantage of having the ability to independently control all NV vents will be shown in the results section.

In addition to the hardware building changes, a DOS-based computer control algorithm was developed and tested. The software control logic was written using QuickBASIC (v4.5) and includes a data file of "NV Control Logic Decisions" for controlling all vents. All feedback sensor inputs were updated every 60 s and changes to vent openings (if required) were made at 3-min update intervals.

NV CONTROL LOGIC DECISIONS

The NV control logic adjusted the SS and NS curtains and the ridge vent in response to the indoor climate relative to the desired set-point temperature and relative humidity. The SS and NS curtain opening levels were controlled by the average of three SS and NS temperature sensors, respectively (fig. 5). Both the SS and NS curtains were controlled proportionally, based on the absolute error between the SS and NS average temperatures and the set-point temperature. In general, an absolute error of 5°C caused full-curtain motion. For example, if the SS curtain was open the full 1.15-m width, and the average SS temperature was 5°C below set-point, the proportional control logic would cause the curtain to fully close. Likewise, a 2.5°C average SS temperature below set-point would cause the curtain to close 50% of its current level. If the SS curtain was open 60 cm, and a 2.5°C temperature error occurred, the curtain would close 30 cm, or half of it's current opening. In this way, the building could respond quickly to abruptly changing weather conditions.

The ridge vent was controlled based on several factors, but primarily it was a function of the combined opening status of the SS and NS curtains. If the combined opening level of the SS and NS curtains was greater than 20 cm, the ridge vent was allowed to operate fully open. Between a combined SS and NS curtain opening level of 5 and 20 cm, the ridge vent was commanded to close to a 50% opening level. If the combined SS and NS curtain opening level was below 5 cm, the ridge vent was commanded to fully close, at which point the barn entered a "purge mode."

The purge mode was used to prevent excessive moisture build-up in the building and is best described as a variable ventilation mode. In purge mode, the inside relative humidity was used to indirectly control indoor air quality. In purge mode, the set-point relative humidity was compared with actual inside relative humidity. If the inside relative humidity reached a level 5% above the desired set-point relative humidity, the building was allowed to ventilate in an attempt to keep indoor air quality at acceptable levels. When commanded to ventilate during purge mode, the average SS and NS temperatures were scanned to determine the zone at the highest temperature. Once this was determined, the curtain on the warmer of the two zones was allowed to open 10 cm, followed by an opening of the ridge vent to the same 10-cm level. The building was then allowed to ventilate with these two openings for a period of 60 s. At the end of 60 s, the ridge vent was closed first, then the opened curtain was closed. The purge process continued at 3-min intervals until the building had sufficiently warmed, causing either the SS or NS curtains to again proportionally open. This technique worked quite well in controlling for both inside average NAL temperature and relative humidity, during those periods where the building was fully closed, causing the purge mode to activate.

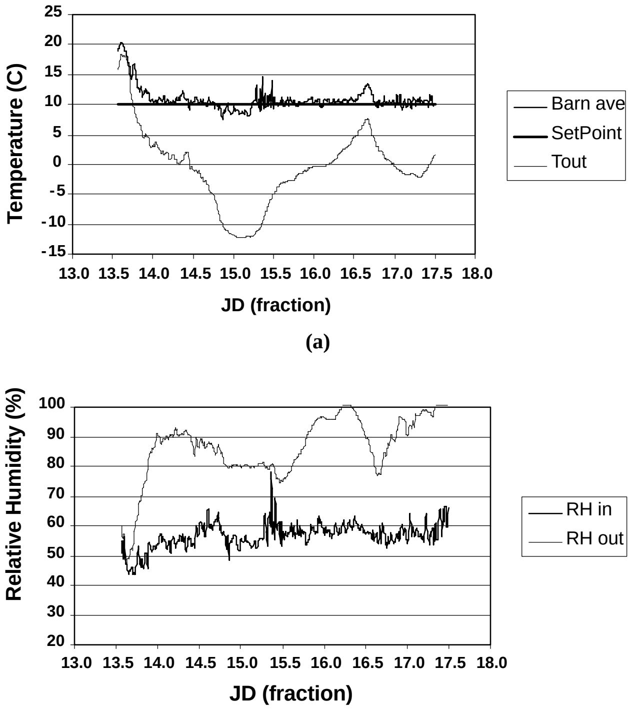
Great care was taken to not allow the building to ventilate with a single opening. For example, if one of the curtains had fully closed, then the ridge vent was adjusted proportionally based on the guidelines given previously. If both curtains were fully closed, then the ridge vent was closed as well and the building entered purge mode control. This approach prevented short-circuiting of the ventilation air, and especially down-drafting through the ridge vent. If both curtains were closed, and the ridge vent had been left open, a portion of the ridge vent would behave as an inlet, forcing cold high-speed air down into the animal zone. To prevent short-circuiting from occurring, the NV control logic monitored the opening level of all vents.

Each vent opening level was monitored by calibrating the time it took the actuators to both close and open each respective vent. The code developed then recorded "run-times" for each of the vents and back-calculated the actual opening level of each vent. Once every three days, all vents were allowed to fully close to "reset" the curtain opening level to a known value. In this way, vent openings were being constantly re-calibrated. This method worked very well. Originally, multi-turn potentiometer sensors were developed and attached to both the SS and NS curtains and the ridge vent to record and sense opening level status. This method worked very well but the added sensing complicated the control system and was abandoned.

The NV control logic described was developed over a period of two years. Several versions of the logic were developed and refined with results as shown in the next section.

RESULTS AND DISCUSSION: OBJECTIVE TWO

Two specific periods are shown to illustrate NV control performance with the design and logic modifications outlined previously. The first period represents a four-day January period where outside temperature varied between +18.5°C and -13°C. This period was chosen because of its obvious extremes in outdoor conditions. The second period chosen was a 44-day spring period where outdoor temperatures varied between a low of -13°C and a high of 32.5°C.



(a)

(b)

Figure 6. Example (a) average inside barn temperature and (b) relative humidity levels relative to outside conditions for a typical cold-weather period (JD = Julian Day).

Both periods were representative of extreme changes in weather patterns that an NV barn should be expected to control. Each of the two periods are discussed below.

COLD WEATHER CONTROL CHARACTERISTICS

Figure 6 summarizes the four-day January period (JD = 13.5 to JD = 17.5) where the outdoor temperature ranged from +18.5°C to -13°C. For this period, the indoor climate had a set-point temperature of 10°C. The average barn temperature, for periods when the outside temperature was below set-point temperature, was 10.6°C with a standard deviation of 1.1°C. The inside relative humidity, with a set-point of 60%, was on average 57% with a standard deviation of 3.6%.

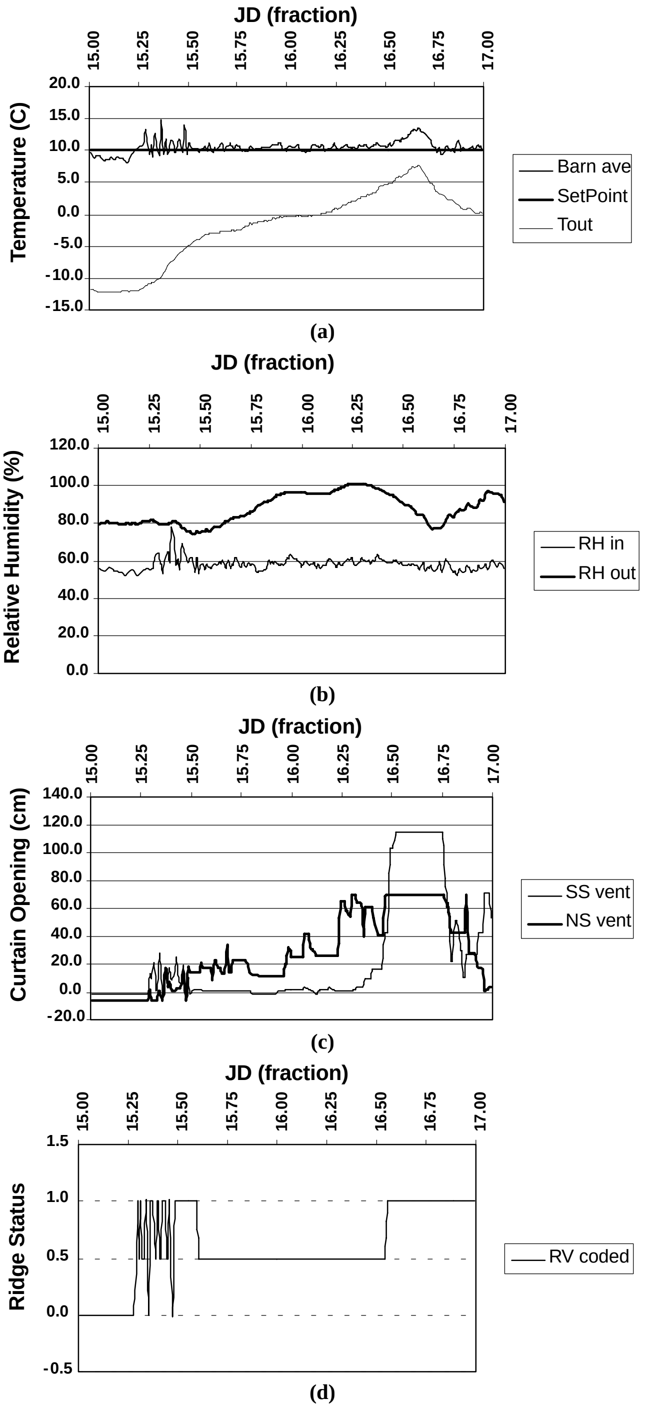


Figure 7. Close-up two-day (JD = Julian Day) analysis showing (a) average inside barn temperature control, (b) inside relative humidity control, (c) south- and north-side curtain positioning, and (d) ridge-vent status (0 = closed, 0.5 = proportionally open, 1 = fully open). When all vents were closed (JD15 to JD15.25), the building was operating in purge mode.

Curtain and ridge vent control for the subset period of JD15 to JD17 is shown in figure 7. Figure 7c highlights both the NS and SS curtain control levels and figure 7d highlights the ridge vent control. During the cold period between JD15 and JD15.25, the ridge vent and both curtains were closed. During this same period, and as a standard control logic decision, the ridge vent and the warmest zone curtain were purging the barn to maintain humidity control. As the outside temperature warmed, as shown for the period beyond JD15.25, the NS and SS curtains along with the ridge vent were commanded to open proportionally until JD16.5, at which time all three vents were allowed to completely open in response to a significant warming trend.

During the period between JD15.5 and JD16.5, the wind (not shown) was from the south, and thus as shown in figure 7c, the SS curtain lagged behind the NS curtain in opening level. This phenomenon, as described previously, is absolutely necessary for proper control of NV barns. If during the winter months a warming trend is experienced, and this warming trend is a result of summer-direction winds, then the barn must have the ability to control the ventilation process from the predominant winter-side vents. A blanket policy of closing off predominant winter-side vents must not be allowed if the desire is to maintain climate control in the barn.

MILD WEATHER CONTROL CHARACTERISTICS

Figure 8 summarizes the 44-day weather period (JD71 to JD115) when the outdoor temperature varied between a low of -13°C and a high of 32.5°C. This period represented an

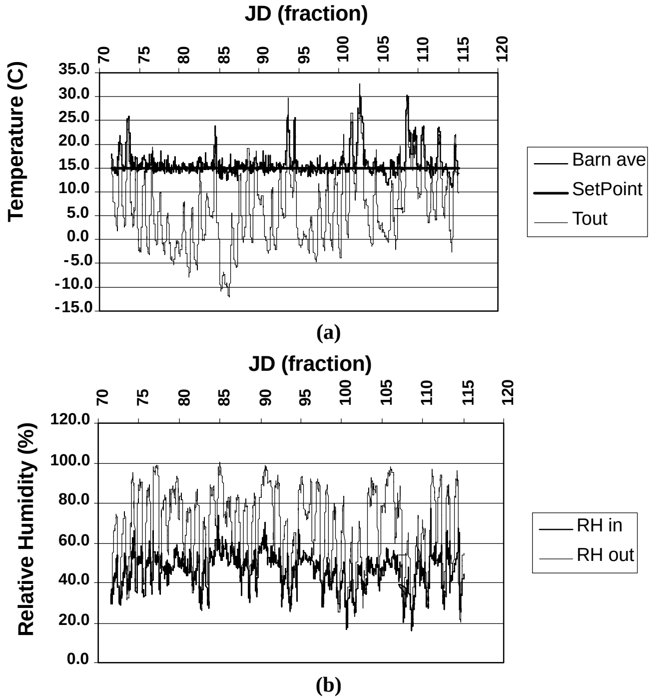
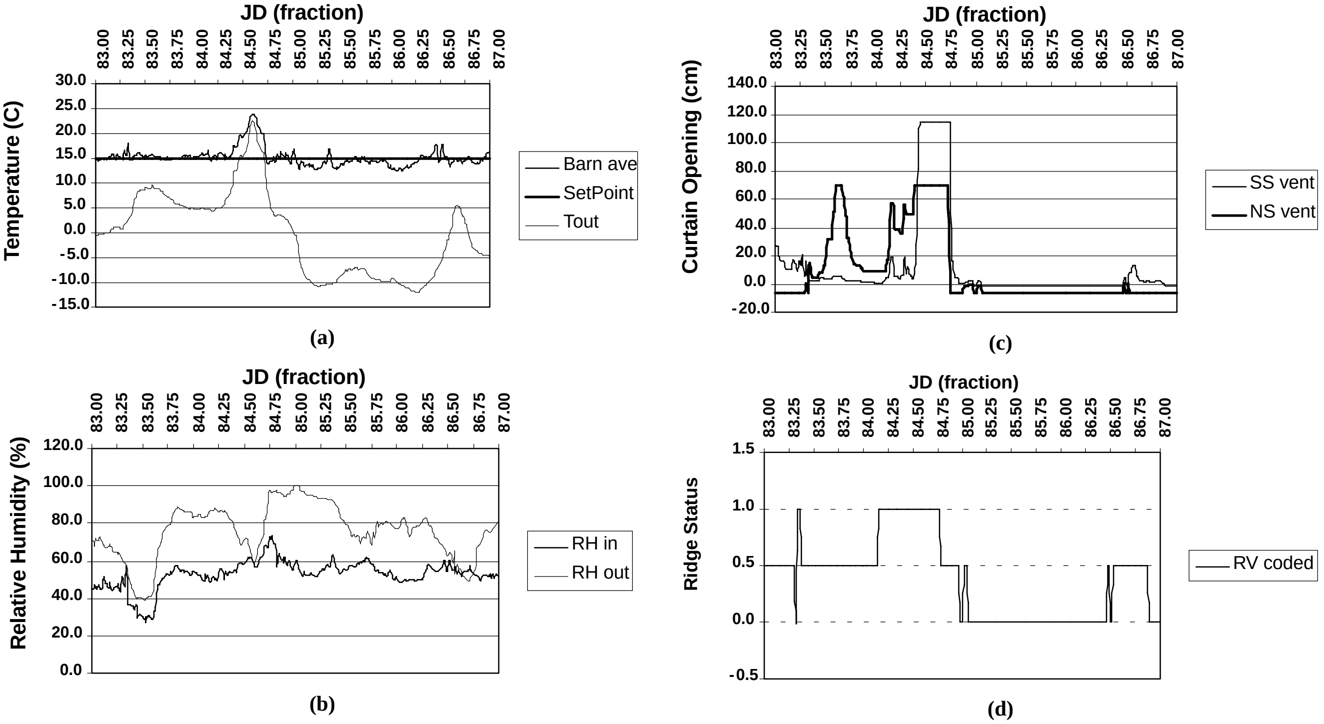


Figure 8. Example (a) average inside temperature and (b) relative humidity levels relative to outside conditions for a mild-weather period (JD = Julian Day).



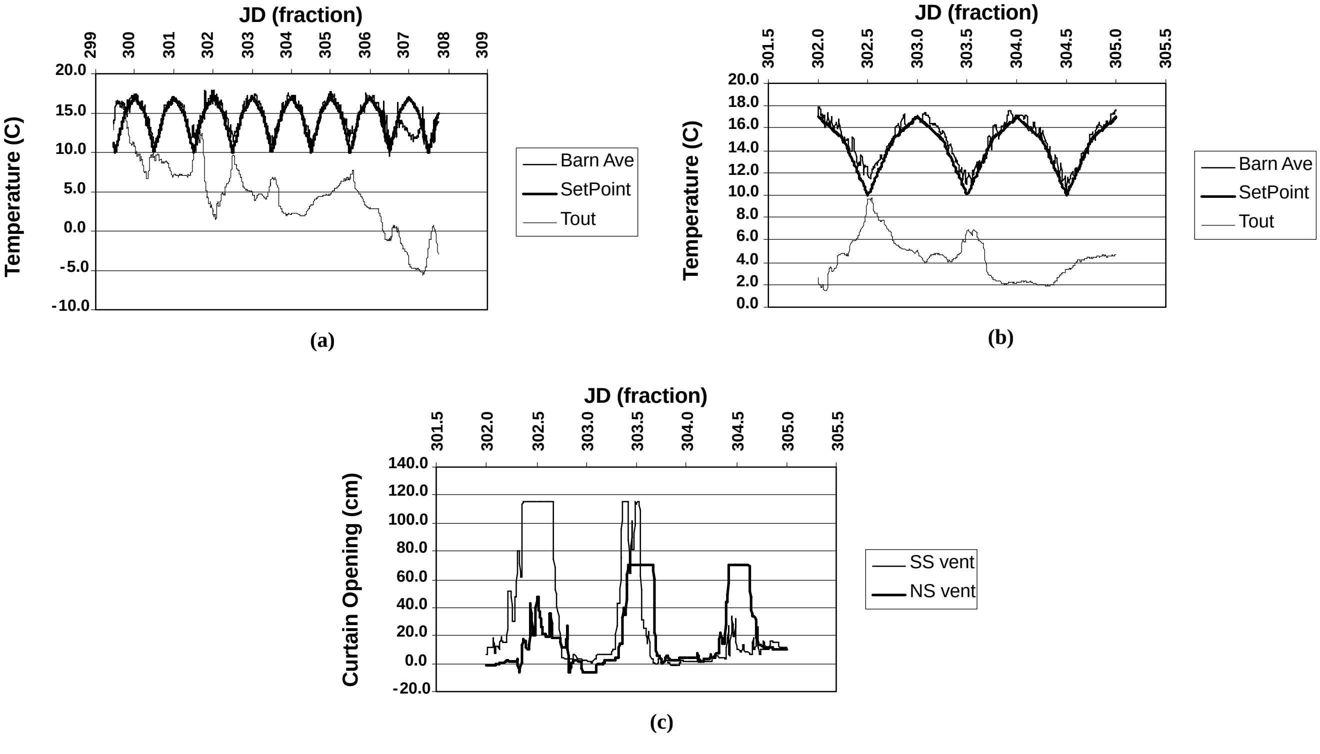
(a) (c)

(b) (d)

Figure 9. Example (a) average inside temperature and (b) relative humidity levels relative to outside conditions for a mild-weather period (JD = Julian Day). When all vents were closed (JD85.25 to JD86.5), the building was operated in purge mode.

excellent example of the extreme mild-weather conditions that all mid-western NV barns face. During this period, the set-point conditions were 15°C and 60% relative humidity. For this entire 44-day period, the barn average temperature, for periods where the outside temperature was below the set-point temperature, was 15.1°C with a standard deviation of 1.1°C. The inside relative humidity, with a set-point of 60%, was on average 47.8% with a standard deviation of 7.3%.

Curtain and ridge vent control for the subset period of JD83 to JD87 is shown in figure 9. Figure 9c highlights both the NS and SS curtain control levels and figure 9d highlights the ridge vent control. During the warm-up period between JD83 and JD84.5, both curtains and the ridge vent were



(a) (b)

(c)

Figure 10. Flexibility in NV control logic demonstrated via a diurnal change in (a,b) building set-point temperature and (c) the curtain control required to maintain the desired set-point (JD = Julian Day).

proportionally opened to their full potential. As the outdoor climate progressively cooled between JD84.5 and JD86.25, the ridge vent and both curtains were allowed to proportionally close. Again, at the time when all vents were closed (JD85.25 to JD 86.25), the building was operating in purge mode for humidity (and thus air quality) control.

During the period between JD83.25 and JD84, the winds (not shown) were from the south, and thus as shown in figure 9c, the SS curtain lagged significantly behind the NS curtain in opening level for the reasons described previously.

VARIABLE SET-POINT CONTROL CHARACTERISTICS

To further demonstrate the control logic, a diurnal set-point temperature variation was programmed as shown in figure 10a. A three-day trend is shown for analysis (figs. 10b,c). The set-point temperature was allowed to vary between a low of 10°C at noon each day to a high of 17°C at midnight, with variations in between as shown. The barn average temperature followed the desired set-point temperature very well and was the result of continuous variations in the NS and SS curtains as shown in figure 10c (ridge vent control not shown for brevity). The benefit of independent vent control is very apparent relative to outside weather influences. For example, during JD302 the winds were predominantly from the north, thus causing the NS curtain to lag behind the SS curtain. In contrast to this, the opposite trend occurred during JD304, where the predominant winds were from the south, causing the NS curtain to open more aggressively relative to the SS curtain.

Figure 11 and table 2 summarize the level of control achieved during the three periods described above. During the winter period (fig. 6a data set), the set-point temperature was maintained, without supplemental heating, at ±3°C for 96.7% of the time (fig. 11a). During the spring period (fig. 8a data set), the set-point temperature was maintained at ±3°C for 97.4% of the time (fig. 11b). During the variable set-point

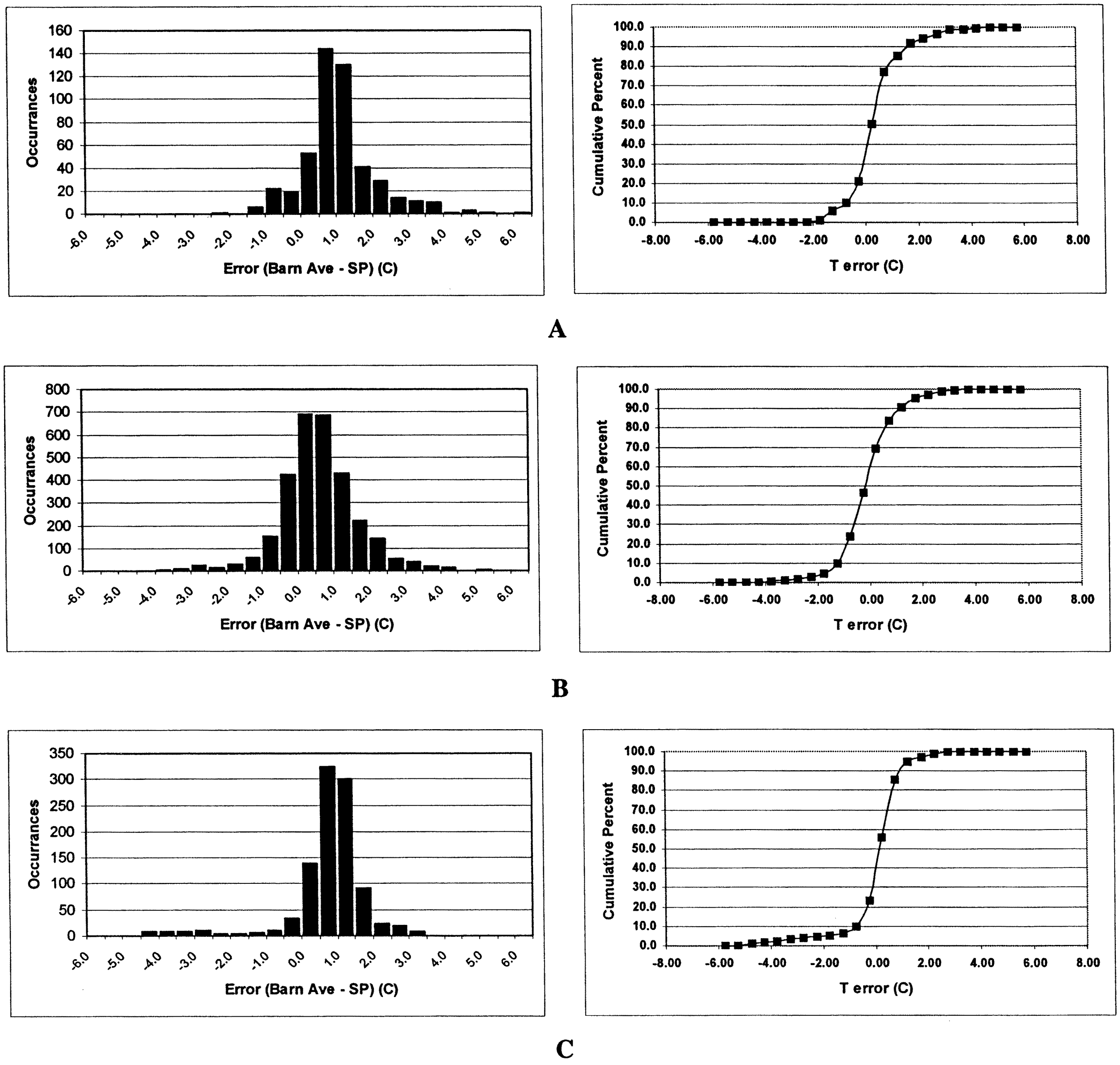


Figure 11. Temperature error histograms and cumulative percentages for (a) winter (fig. 6a data set), (b) spring (fig. 8a data set), and (c) variable SP test periods (fig. 10a data set). Temperature error defined as (Barn Ave Temp - SP) and only includes those periods when Tout < SP since no cooling control available.

Table 2. Temperature errors recorded for the three distinct control periods.

	Percent Time in Each Error Band		
	Control Period		
Error Band[a]	Winter	Spring	Variable SP
-1 to 1	67.3	59.8	75.8
-2 to 2	90.1	90.8	91.9
-3 to 3	96.7	97.4	96.2
-4 to 4	99.0	99.6	98.3

[a] Error band defined as (Barn Ave T - SP) (°C).

period (fig. 10a data set), the set-point temperature was maintained at ±3°C for 96.2% of the time (fig. 11c).

SUMMARY

In summary, NV barns can be controlled at a very high level. Relatively simple control logic decisions that independently control vents, based on properly positioned zone-averaged feedback sensors, can drastically improve the level of NV control achieved. Key parameters that need to be considered include sensor placement, the size of zone volume controlled for, independent actuation of vents, proportional control of vents, and control logic to prevent short-circuiting of fresh-air through sidewall vents and down-drafting through the ridge vent.

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REFERENCES

Choiniere, Y., J. A. Munroe, and A. Suchorski-Tremblay. 1992. “NatVent” software predictions versus full-scale estimates of wind induced natural ventilation in a swine barn. CSAE Paper No. 92202. Saskatoon, SK: CSAE.

Hales, S. 1758. A Treatise on Ventilators. London, England.

Hoff, S. J. 2001. Assessing air infiltration rates of agricultural-use ventilation curtains. *Applied Engineering in Agriculture* 7(4): 527-531.

MWPS, 2001. Swine Breeding and Gestation Handbook. Ames, Iowa: Iowa State University, Midwest Plan Service.

Naas, I. A., D. J. Moura, R. A. Bucklin, and F. B. Fialho. 1998. An algorithm for determining opening effectiveness in natural ventilation by wind. *Transactions of the ASAE* 41(3): 767-771.

Van’t Klooster, C. E. 1996. Animal-based control algorithm for natural ventilation in pig houses. *Transactions of the ASAE* 39(3): 1127-1133.

Zhang, J. S., K. A. Janni, and L. D. Jacobson. 1989. Modeling natural ventilation induced by combined thermal buoyancy and wind. *Transactions of the ASAE* 32(6): 2165-2174.

Zhou, H., J. J. R. Feddes, J. J. Leonard, and R. Borg. 1997. Application of a computer model for naturally ventilated livestock buildings in Alberta under summer conditions. *Canadian Agricultural Engineering* 9(4): 327-334.