VARIABLE RATE HEATER CONTROL FOR LIVESTOCK SPACE HEATING

D. M. Van Utrecht, S. J. Hoff, J. D. Harmon

ABSTRACT. *An unvented liquid propane–gas (LP) space heater, often used in animal housing, was modified to provide automated variable heat output. As manufactured, the heater had manually–adjusted output settings between 14.7 and 29.3 kW (50,000 and 100,000 Btu/h). The heater was modified by adding a stepper motor and speed reducer to the manual proportioning valve to provide continuous and automated heater output adjustment between 14.7 and 29.3 kW.*

Experiments were conducted to compare animal occupied zone (AOZ) velocities, AOZ temperatures, and fuel consumption using on/off and automated variable control modes. These experiments were conducted using inside set point and ambient air temperature differences of 14 and 28°C (25 and 50°F). All experiments were conducted in the Air Dispersion Laboratory at Iowa State University.

Adding automated variable control reduced the AOZ temperature fluctuations from 5.3°C (on/off) to 1.1°C (9.5 to 2.0°F). In the AOZ, the standard deviation across the entire test room was reduced from 1.4°C (on/off) to 0.3°C (2.6 to 0.5°F). The AOZ airspeed fluctuations were reduced from 10 cm/s (on/off) to 2 cm/s (20 to 4 ft/min). No differences were found in fuel consumption. Results indicate a need for heaters capable of continuous adjustment to even lower energy output levels.

Keywords. *Automated control, Space heat, Liquid propane, Efficiency.*

Maintaining a constant and uniform temperature in the animal's occupied zone (AOZ) during cold weather can be challenging. Current housing systems utilize space heaters with simple on/off control due primarily to ease of operation and control. This control strategy creates peaks and valleys in room temperature and depending on pig age, could be a detriment to efficient growth and health. In the swine industry, supplemental heat is usually required in farrowing, nursery, and wean–to–finish buildings.

Winter ventilation rates are kept at a minimum to reduce the amount of supplemental heat required. When supplemental heat is required, indoor temperatures tend to rise rapidly, often above the desired set point. The room temperature is then allowed to fall below set point a fixed amount before the supplemental heat source is reactivated. Increasing this temperature difference prevents rapid repetitive cycling of the supplemental heat source. Unfortunately, this strategyresults in significant differences between the high and low room temperature within the AOZ. Research has shown that high cyclic temperatures can have an adverse effect on swine growth (Feddes et al., 1996).

OBJECTIVES

The objective of this research project was to modify a conventional space heater to make it capable of automated variable heat output and to evaluate the AOZ temperature and airspeed control performance and fuel consumption compared to on/off control.

MATERIALS AND METHOD

The Air Dispersion Laboratory (ADL) was used for this research project. Details related to the design and capabilities of the ADL can be found in Hoff et al. (2000). Set–up details required in the ADL for conducting this research project are given below.

SIMULATING HEAT PRODUCTION

Sensible heat production of animals occupying the test chamber was simulated using six–660 W (2,252 Btu/h) cone resistance heaters. One heater was placed within each of six pens under a perforated aluminum dome. The heaters simulated the sensible heat production from 22–23 kg (50 lb) pigs per pen (132 pigs total). The floor plan of the test chamber and location of each of the six pens in relation to the heater is shown in figure 1.

HEATER MODIFICATIONS

From the factory, the supplemental heater used for this research project was capable of manual adjustment from 14.7 and 29.3 kW (50,000 and 100,000 Btu/h) and was controlled as an on/off heater (see table 1). The heater was modified to provide variable output control by installing a stepper motor

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The authors are David M. Van Utrecht, former Graduate Research Assistant, **Steven J. Hoff, ASAE Member Engineer,** Associate Professor, and **Jay D. Harmon, ASAE Member Engineer,** Associate Professor, Agricultural and Biosystems Engineering Department, Iowa State University, Ames, Iowa. **Corresponding author:** Steven J. Hoff, 206B Davidson Hall, ABE Dept., Iowa State University, Ames, IA 50011; phone: 515–294–6180; fax: 515–294–2255; e–mail: hoffer@iastate.edu.

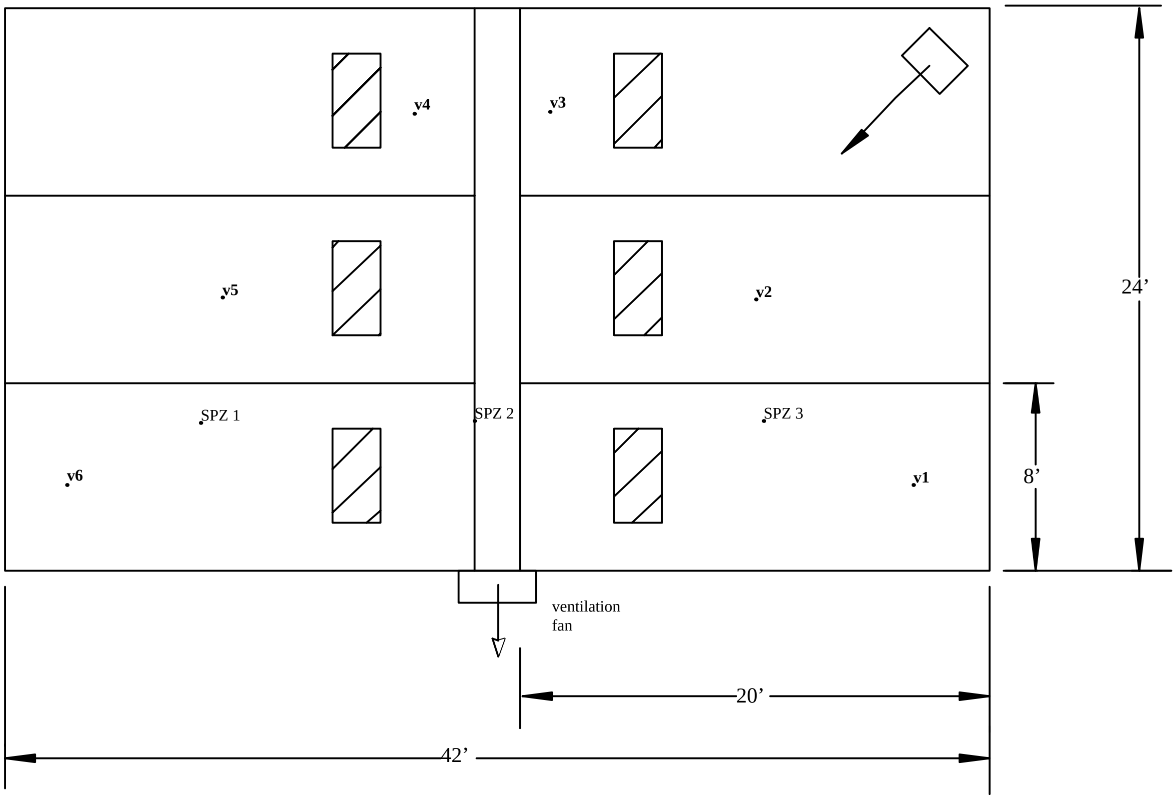


Figure 1. Floor plan of test chamber showing relationship between AOZ temperature and airspeed measurements (v1 to v6 for zones 1 to 6, respectively) and the set–point temperature zones (SPZ). AOZ sensors positioned 76 cm (30 in.) from the floor and SPZ sensors positioned 1.2 m (48 in.) from the floor. Simulated pig heaters shown as cross–hatched rectangles. Ventilation air exhausted using under–floor extraction through the walkway plenum shown. Fresh–inlet air was supplied through ceiling inlet diffusers.

and speed–reducing gearbox attached to the factory supplied manual proportioning valve (fig. 2). This modification allowed for accurate and automated positioning of the gas supply valve in 1,900 discrete steps over a 90–degree range of motion.

The stepper motor was controlled with an MX 2.0 controller card (fig. 3). The controller card is accessed through an 8–bit data processing card placed in a PC (Model AIO8G–P; Industrial Computer Source, San Diego, Calif.). An additional 8–bit data processing card provided temperature input (Model AIO8G–P; Industrial Computer Source, San Diego, Calif.). The automated variable control (AVC) logic was written in QuickBASIC® installed on the PC. This platform provided a convenient and centralized method to control, monitor, and store performance data.

Table 1. Liquid propane unit space heater specifications used for variable control modifications.

Heater Property		Manufactured Specification
Maximum input		29.3 kW (100,000 Btu/h)
Minimum input		14.7 kW (50,000 Btu/h)
Ventilation air to support combustion		680 m^3/h (400 ft^3/min)
Inlet gas supply pressure Acceptable at inlet of heater for purpose of input adjustment	Maximum	3,359 Pa (13.5 in. W.C.)
	Minimum	2,737 Pa (11 in. W.C.)
Net weight		29.5 kg (65 lb)
Fuel consumption per hour	Maximum	2.2 kg (4.6 lb)
	Minimum	0.9 kg (2.3 lb)
Dimensions (L × W × H)		75 × 36 × 46 cm (29.5 × 14.25 × 18 in.)
Motor characteristics		Bell Bearing 93 W (1/8 hp), 1100 rpm, 1.4 amp
Electrical supply		115 V.A.C., 60 Hz, 1 Phase
Igniter amp draw (for 23–s duration)		4–7 amps

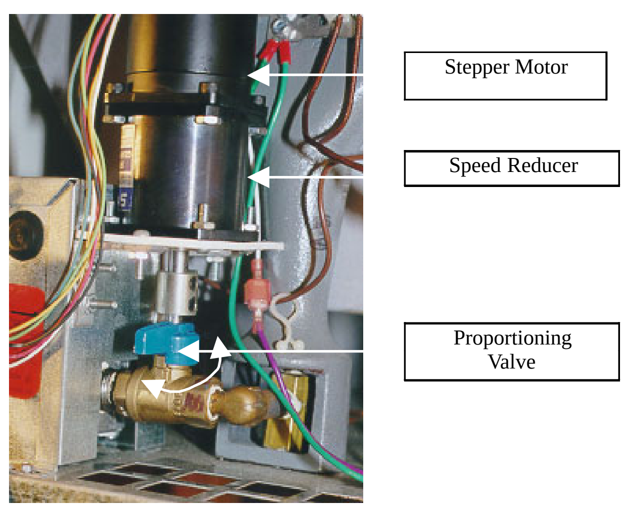


Figure 2. Manual proportioning valve as a standard feature of the heater with modifications attached for automated variable control (AVC).

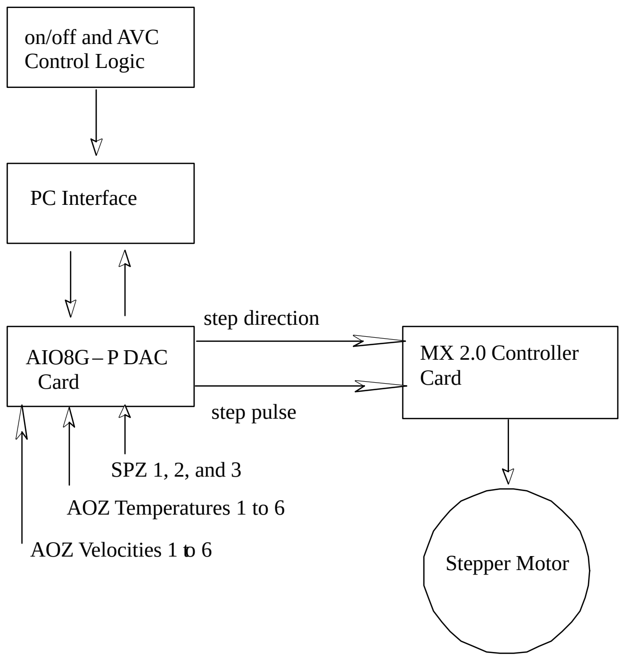


Figure 3. Data acquisition and stepper motor setup for data collection and automated control logic.

DATA COLLECTION AND HEATER CONTROL LOGIC

TEMPERATURE AND AIRSPEED SENSING

Three temperature transducers (Model AD592; Analog Device, Inc) were placed 1.2 m from the slatted floor of the test chamber as shown in figure 1. These three locations were defined as the set point zone (SPZ). The average of SPZ 1, SPZ 2, and SPZ 3 were used to control the heater in both on/off and AVC modes. In addition, each of the six pens contained a T–type thermocouple and an omni–directional airspeed sensor (Model 8470; TSI, Inc, St Paul, Minn.), positioned 76 cm above the floor, one set in each of the six pens at the locations shown in figure 1. These six locations were defined as the animal occupied zone (AOZ) for each pen. As shown in figure 1, each of the six locations is labeled 1 to 6. Results refer to the SPZ, AOZ, and the six "zones" within the test chamber.

HEATER EFFICIENCY

Fuel consumption of the unit heater was monitored with an American AL–425 Aluminumcase Meter. A custom fit volumetric flow totalizer with contact closure output allowed the data acquisition and control system (Model CR–10, Campbell Scientific, Inc.; Logan, Utah) to measure the volume of fuel consumed. The meter had a resolution of 0.03 m^3 and an accuracy of ±1%.

HEATER CONTROL LOGIC

The control logic for on/off control used a solid–state, normally open relay to activate and deactivate the heater. For all on/off control experiments, the heater was activated at an average room temperature 1° below set point and deactivated once the average room temperature reached 1° above the set point. For all on/off experiments, the heater valve was fixed for 29.3 kW (100,000 Btu/h) output, consistent with a production facility of this size for typical Iowa heating requirements. The on/off control logic, relative to the average SPZ (T_{spz}) and set point (SP) temperatures, is defined below:

Error = (SP – T_{spz})
If (Error < 0.6°C) Then Deactivate Heater
If (Error >= 0.6°C) Then Activate Heater

During on/off control experiments, control decisions were made every 60 seconds.

The AVC control logic used a combined proportional–derivative control with a rule–based decision scheme to control the percent valve opening (PVO). The AVC control logic, relative to the average SPZ (T_{spz}) and set point (SP) temperatures, is defined below:

Error = (SP – T_{spz})
Delta Error = (Current Error – Previous Error)
PVO = PVO + B*(Error) + C*(Delta Error)
B,C = control constants

A deviation from the desired set point (Error) caused the proportioning valve to move, with the degree of movement tempered by the current error relative to the previous error (Delta Error), or, by pre–set decision–based rules. The objective was to maintain the absolute value of the error within 0.14°C (0.25°F). The decision–based rules used to override any of the PVO commands were as follows:

If Error > 1.7°C (3.0°F), PVO = 100% (29.3 kW).
If Error < –1.1°C (–2.0°F) and PVO = 0% (14.7 kW), the heater was deactivated.

During AVC control experiments, decisions were made every 240 seconds. This control update interval was tested extensively and found to be the shortest time required for a control decision to be sensed properly in the test chamber.

HEATER OUTPUT CHARACTERISTICS

A series of test runs were conducted to characterize the performance of the heater. In particular, the effective range of heater output versus valve position was determined to define the effective range of control decisions. The temperature change through the heater (ΔT) with percent valve opening (PVO; 0 to 100%) was measured with temperature sensors placed at the air inlet and outlet of the heater. Heater output was then characterized as the temperature change (ΔT, °C) as a function of PVO as shown in figure 4.

As shown in figure 4, changing the valve position at the extreme ends of the range of motion had little or no effect on heater output. This information was used in the control logic to limit the range of decisions made. For example, if the control logic required a change from 10 to 5% opening, this instruction was ignored since a change in this range had no effect on the output of the heater.

EXPERIMENTS CONDUCTED

Experiments were conducted to compare the thermal and LP–use performance of AVC versus on/off control. These experiments are described below.

NURSERY BUILDING SIMULATION AT 28°C AND 14°C TEMPERATURE DIFFERENTIALS

The test chamber was configured to simulate a production situation where 22– to 23–kg (50–lb) pigs per pen were

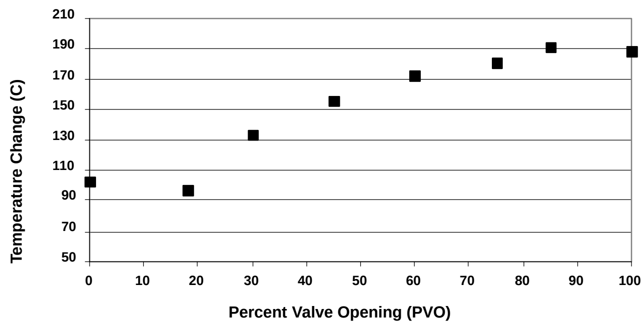


Figure 4. Inlet to outlet temperature difference (ΔT) of the heater as a function of percent valve opening (PVO).

present (132 pigs total). The temperature differentials between outside ambient and set point conditions were set at two levels; 28 and 14°C (50 and 25°F). For each level, the ventilation rate of the test chamber was fixed at 1,560 m^3/h (940 ft^3/min; 7 fresh–air exchanges per hour). Two complete runs at each temperature differential were conducted.

The two temperature differentials tested are important because they represent two unique situations that will arise in practice. When ambient and set point temperatures differ by 28°C, the steady–state supplemental heat requirement falls within the range of 14.7 to 29.3 kW. However, when this differential is reduced to 14°C, the steady–state supplemental heat requirement falls below the lowest output setting (14.7 kW) of the chosen heater. In the latter case, AVC will need to resort to a combined "variable on/off" control mode.

Maintaining a constant ambient temperature in the ADL surrounding the test chamber was not possible, since the outer shell of the test chamber does not yet have controlled cooling capabilities. Opening and closing access doors to the outside controlled the ADL ambient temperature. Although relatively crude, the average ambient temperature for each experiment was near the desired ambient temperature required for the 28 and 14°C differential tests.

Controller Response Characteristics Test

As an indication of controller response time, both the on/off and AVC methods were tested with an abrupt 5.6°C (10.0°F) step change in set point temperature. The total time required to achieve the new set point and control characteristics after set point was achieved were analyzed.

AOZ Airspeed

Automated variable control, with a properly sized heater, will result in a heater that operates continuously during periods where supplemental heat is required. Therefore, the heater's fan system will become an integral part of the minimum ventilation air distribution system. To study this effect, AOZ airspeed levels were compared during on/off and AVC operation. The overall average airspeed in the chamber and the zone average airspeed for the six zones shown in figure 1 were analyzed.

Quantification of Results

Each test was conducted for four hours after reaching steady state conditions in order to obtain accurate airspeed, temperature, and LP–use values. This monitoring time of four hours was studied extensively and it was found to be the shortest monitoring time that yielded accurate and repeatable measurements.

The average, standard deviation, and difference between maximum and minimum values (swing) of the SPZ and AOZ were considered for analysis. In addition, the thermal quality and heater efficiency results were measured as described below.

Thermal Quality

The thermal quality, or closeness of the actual temperature to the desired set point, was examined. For this research, the thermal quality was defined as:

$$\text{Thermal Quality} = \frac{\text{Actual Temperature} - \text{Ambient Temperature}}{\text{Set Point Temperature} - \text{Ambient Temperature}}$$

For all calculations, the set point temperature was prescribed and the actual and ambient temperatures were measured. The actual temperature was either the SPZ or AOZ temperature. The ambient temperature was defined as the air temperature surrounding and entering the test chamber. Therefore, a thermal quality within the AOZ or SPZ could be defined. In either case, a thermal quality of 1.0 implies control at the desired set point.

Heater Efficiency

The fuel consumption of each experiment was continuously monitored over the four hour steady–state period. For all fuel cost comparisons, liquid propane was estimated as $0.50/gallon.

Results and Discussion

28°C Degree Differential (37.8°C Set Point)

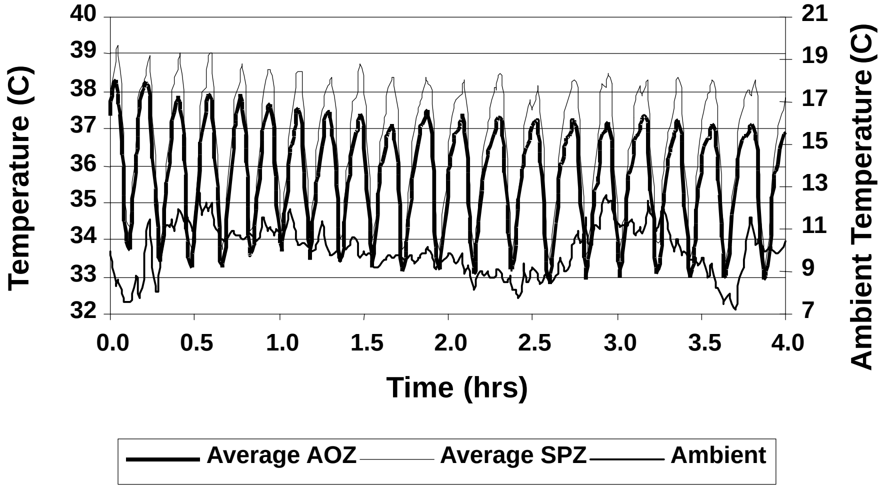
To achieve a 28°C temperature differential, the set point temperature in the test chamber was set to 37.8°C due to ambient temperatures that were near 10°C during the time of testing. Table 2 and figures 5 and 6 summarize the results of this experiment.

The AVC method was able to reduce the temperature swing in the AOZ from an average of 5.3°C (on/off control)to 1.1°C. The temperature swing in the SPZ was reduced from 4.1°C (on/off) to 1.5°C. The standard deviation in the AOZ was reduced from 1.2°C (on/off) to 0.3°C. The AVC method

Table 2. 28°C differential summary (nursery barn heat load, average of two experiments).

	Temperature (°C)			Thermal Quality		
	Avg.	St. dev.	Swing	Avg.	St. dev.	Swing
On/Off control						
SPZ	37.0	1.2	4.1	0.97	0.04	0.15
AOZ	35.3	1.4	5.3	0.91	0.13	0.19
Variable control						
SPZ	37.8	0.3	1.5	1.00	0.01	0.05
AOZ	35.9	0.3	1.1	0.93	0.02	0.04

	LP Consumption		Savings (Cost)/Day	
	M^3/h	$/h	$	$/head
On/Off control	0.82	0.40	(0.47)	(0.004)
Variable control	0.86	0.42		



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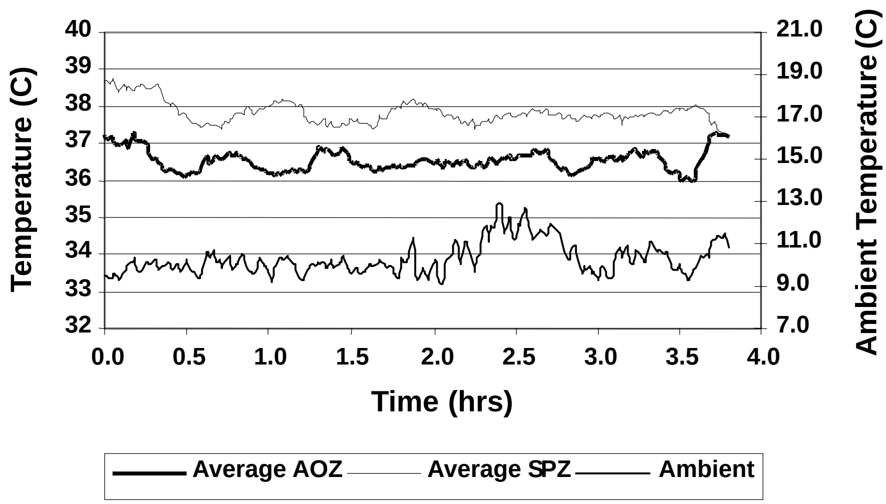

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Figure 5. Average AOZ, SPZ, and ambient temperatures for (a) on/off and (b) AVC control. Set point temperature fixed at 37.8° C (100° F) with a 28° C (50° F) target ambient temperature. Ambient temperature refers to the air temperature surrounding the test chamber.

maintained an average thermal quality of 1.00 in the SPZ, indicating that on average the actual set point temperature and the desired set point temperature were equal at these locations. The average thermal quality in the AOZ was improved by the AVC method, increasing the value from 0.91 to 0.93 relative to on/off control. The average thermal quality swing in the AOZ was reduced from 0.15 (on/off) to 0.05.

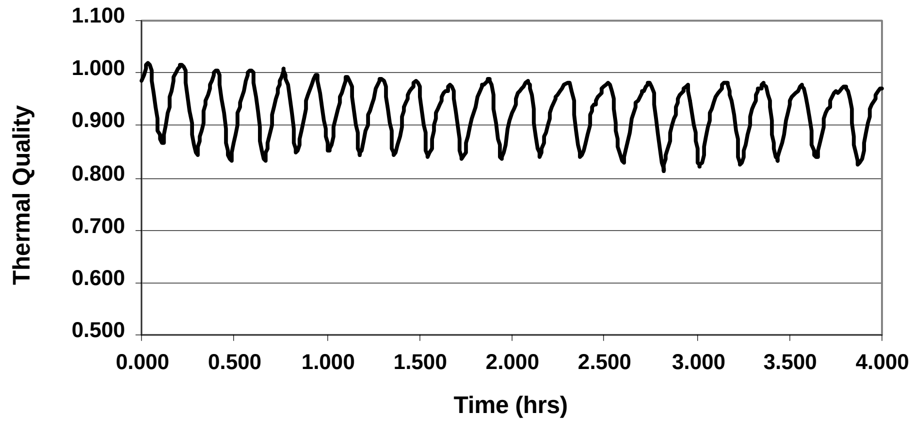
As indicated in table 2, this experiment showed that slightly more energy was consumed with the AVC method. AVC required approximately 0.038 m^3LP/h more, or an additional $0.47/day ($0.004/pig–day) to maintain a set point 28°C above ambient conditions.

The results of this experiment confirm that modifying a space heater from on/off to AVC can significantly improve thermal quality and reduce temperature variation in both the set point and animal occupied zones. The additional fuel requirements were slight and more than offset by the improved thermal quality.

14°C Differential (37.8°C Set Point)

The heater modified for this research had a lower limit heat output of 14.7 kW. This lower limit output was more heat than necessary when the temperature differential was reduced to 14°C. Therefore, for this test the heater resorted to a “variable on/off” control mode in an effort to maintain set point temperature. Results are summarized in table 3 and figures 7 and 8.

The AVC method was able to reduce the temperature swing in the AOZ from an average of 5.3°C (on/off) to 4.9°C. The temperature swing in the SPZ was also reduced from 4.1°C (on/off) to 3.3°C. The standard deviation in temperature control was reduced from 1.4°C (on/off) to



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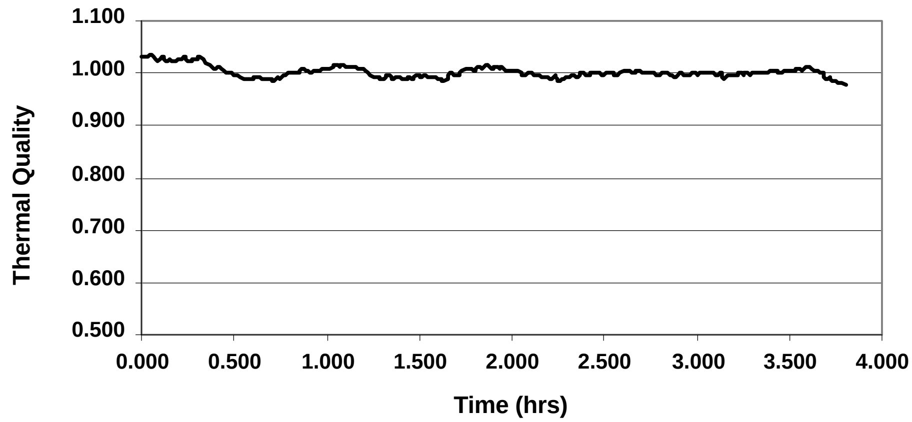


(b)

Figure 6. Thermal quality (ideal = 1.00) in the AOZ for (a) on/off and (b) AVC control methods. Results from control runs shown in figure 5.

0.9°C in the AOZ and from 1.2 to 0.6°C in the SPZ. The AVC method was able to maintain an average thermal quality of 1.01 in the SPZ, indicating that, on average the actual set point temperature and the desired set point temperature were nearly equal. The average thermal quality in the AOZ was also improved by the AVC method, increasing the value from 0.91 to 0.98. The average swing of thermal quality in the AOZ was also reduced by the AVC method, lowering the average value from 0.38 (on/off) to 0.35.

The temperature fluctuation cycle time was approximately 10 min for on/off control. The modified variable control scheme increased the cycle time to nearly 19 min. This increased cycle time was an improvement, but did not solve the problem of cyclic temperatures in the room. A supplemental heat source capable of lower energy output is necessary to supply the required energy without overheating the building.

For this experiment, fuel use decreased with the AVC method. Average fuel consumption decreased by 0.04 m^3LP/h, from 0.65 m^3LP/h (on/off) to 0.61 m^3LP/h, or a savings of $0.39/day ($0.003/pig–day).

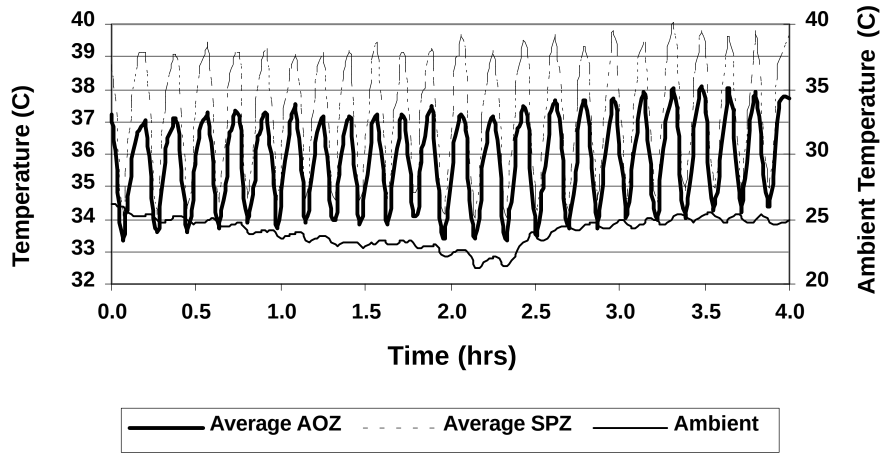
STEP CHANGE CONTROL RESPONSE

The response for both the on/off and AVC control methods to a step–change in set point temperature is summarized in figure 9. The results indicate that each control method required the same amount of time, approximately 40 min, to reach the new set point. This result was expected since the AVC method commands full heater output (29.3 kW) when the deviation from set point is more than 1.7°C. Likewise, for all on/off control experiments, the heater output setting was fixed at 29.3 kW. As shown in figure 9, AVC operation

Table 3. 14° C differential summary (nursery barn heat load, average of two experiments).

	Temperature (°C)			Thermal Quality		
	Avg.	St. dev.	Swing	Avg.	St. dev.	Swing
On/Off control						
SPZ	37.3	1.2	4.1	0.96	0.08	0.29
AOZ	36.5	1.4	5.3	0.91	0.10	0.38
Variable control						
SPZ	37.9	0.6	3.3	1.01	0.05	0.24
AOZ	37.5	0.9	4.9	0.98	0.07	0.35

	LP Consumption		Savings (Cost)/Day	
	M^3/h	$/h	$	$/head
On/Off control	0.65	0.31	0.39	0.003
Variable control	0.61	0.30		



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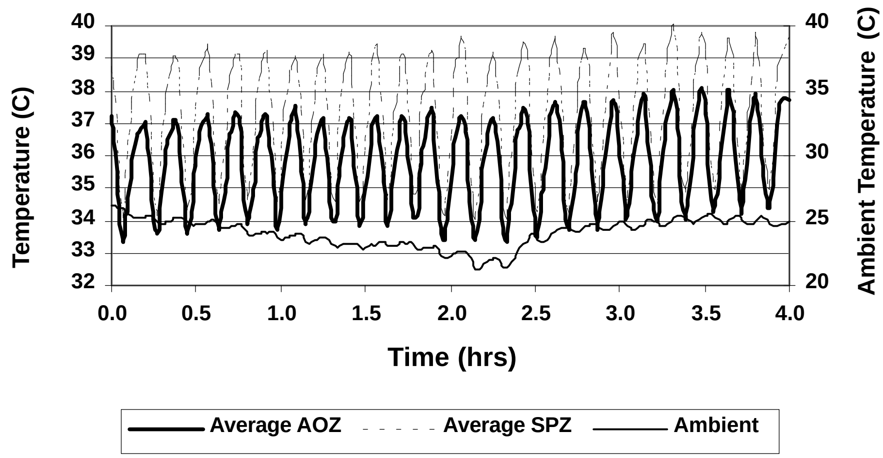


(b)

Figure 7. Average AOZ, SPZ, and ambient temperatures for (a) on/off and (b) AVC control. Set point temperature fixed at 37.8°C (100°F) with a 24°C (75°F) target ambient temperature. Ambient temperature refers to the air temperature surrounding the test chamber.

resulted in a very smooth transition between set points with little fluctuation, unlike the conventional on/off control method.

AOZ Airspeed

Continuous heater use for the AVC method did influence the overall average air velocities in the test chamber. The cyclic operation of on/off control is clearly evident in the average AOZ airspeed as shown in figure 10a. The AVC method reduced the overall AOZ airspeed variability and resulted in a higher average AOZ airspeed (fig. 10b) as compared to on/off control. Average AOZ airspeed swing was reduced from 9 cm/s (on/off) to 1 cm/s. The overall average airspeed increased from 14 cm/s (on/off) to 16 cm/s for the AVC method.

Summary and Conclusions

Four specific conclusions from this study were:

1. A manually adjusted livestock space heater can be modified for automated variable heat output.
2. Automatic variable control reduced the maximum temperature swing in the AOZ by an average of 4.2°C as compared to on/off control for thermal conditions requiring constant heat input.
3. Constant blower operation of the AVC method results in slightly higher average AOZ air velocities. Intermittent heater blower operation produced fluctuations of 9 cm/s in the AOZ where the AVC method reduced this to 1 cm/s.
4. Small supplemental heat loads require space heaters capable of lower energy output than conventional space heaters.

Conventional space heaters capable of multiple energy output levels can be modified to provide automated variable output. Combining a simple stepper motor, speed reducer, relay, and appropriate control logic allows for implementation of various control schemes. The equipment has proven to be simple, safe, and reliable. Mass production of such a system should be economically feasible.

If AVC is implemented commercially, more attention to heater placement will need to be made since the heater's distribution system will become an integral part of the minimum ventilation air distribution system.

While there is a lack of research proving the advantages of constant room temperatures, improving the comfort of the animal is always desirable if it does not impose a significant economic burden. This research has proven that AVC is capable of reducing temperature variation in the set point zone and the animal occupied zone with essentially the same energy input.

The AVC method was not as capable of maintaining constant room temperature when small supplemental heat requirements, relative to minimum heater outputs, were present. A heater capable of lower heat output would help to alleviate this problem so the control logic could use AVC without resorting to “variable on/off” control.

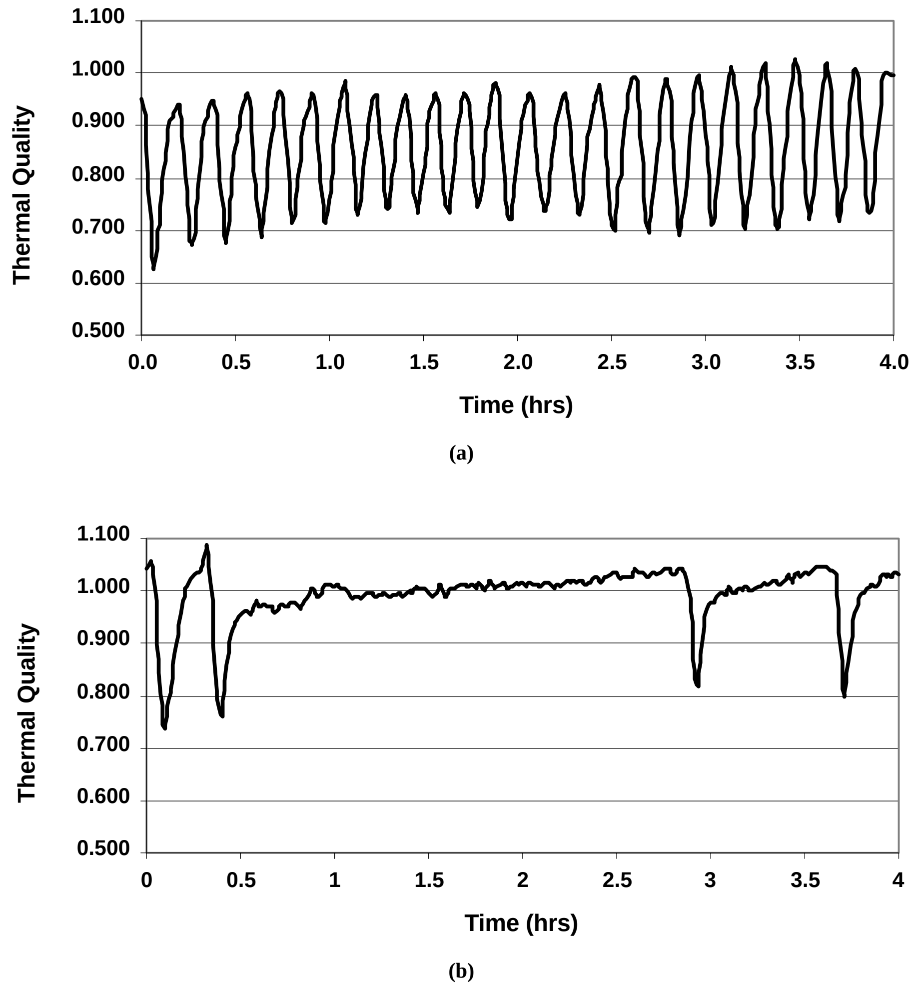
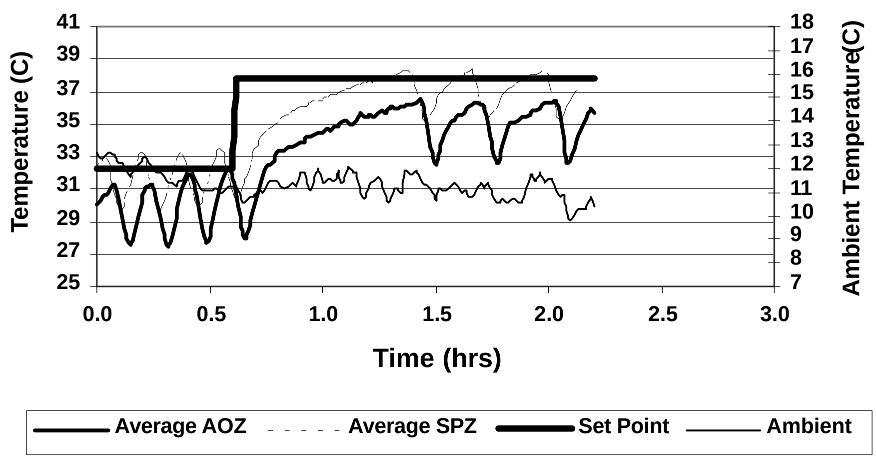


Figure 8. Thermal quality (ideal=1.00) in the AOZ for (a) on/off and (b) AVC control methods. Results from control runs shown in figure 7.



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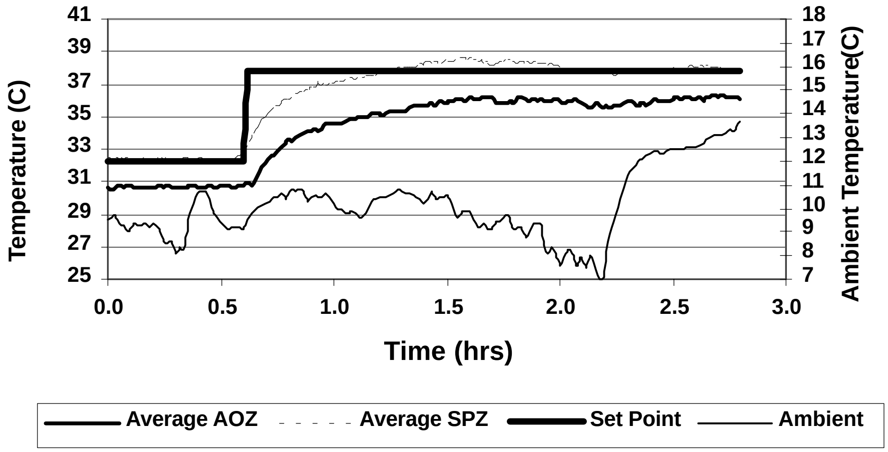
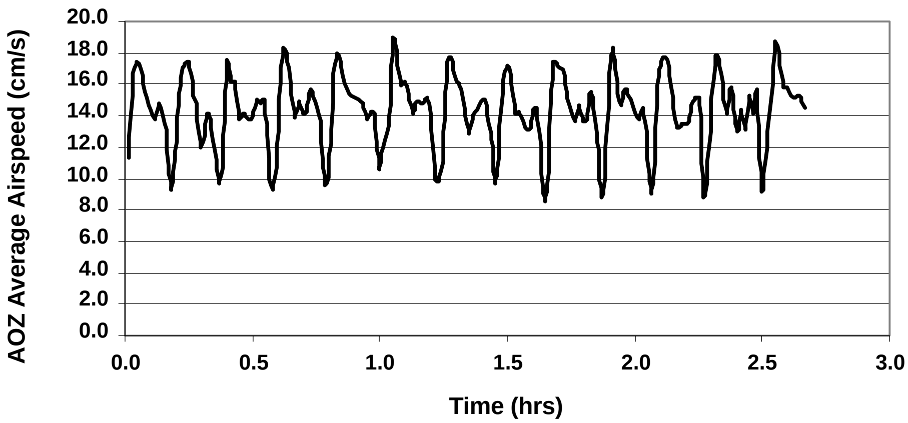


(b)

Figure 9. Response characteristics for (a) on/off and (b) AVC control methods for a 5.6°C (10°F) step change in set–point temperature. Set point changed from 32.2 to 37.8°C (90 to 100°F), 0.60 h after steady–state conditions reached for the 32.2°C set point temperature. Target ambient temperature was 10°C (50°F).



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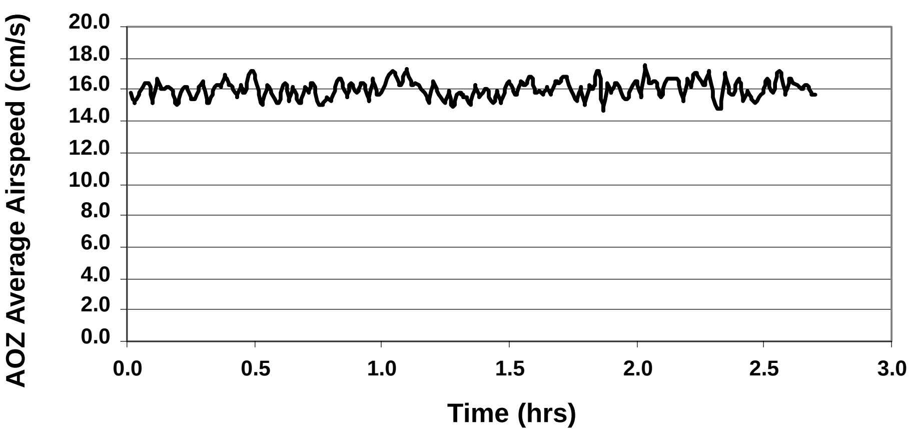

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Figure 10. Average AOZ airspeeds for (a) on/off and (b) AVC control methods. Average airspeeds determined from the six measurement zones shown in figure 1.

References

Feddes, J. J., A. M. Parkhurst, J. A. DeShazer, and A. Blecha. 1996. Factor analysis of growing pigs' responses to high cyclic and constant temperatures. *Transactions of the American Society of Agricultural Engineers* 39(5): 1847–1851.

Hoff, S. J, D. M. Van Utrecht, J. D. Harmon, and D. W. Mangold. 2000. A general–purpose laboratory for evaluating livestock ventilation systems. *Applied Engineering in Agriculture* 16(6): 701–710.