Humidity control for swine buildings in cold climate - Part II: Development and evaluation of a humidity controller

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[1]*Prairie Swine Centre Inc., P.O. Box 21057, 2105 – 8th Street East, Saskatoon, SK, Canada S7H 5N9;* [2]*College of Agriculture, University of Saskatchewan, Saskatoon, SK, Canada S7N 5A8; and* [3]*Department of Agricultural & Bioresource Engineering, University of Saskatchewan, Saskatoon, SK, Canada S7N 5A9*

Guo, H., Lemay, S.P., Barber, E.M., Crowe, T.G. and Chénard, L. 2001. **Humidity control for swine buildings in cold climate - Part II: Development and evaluation of a humidity controller**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **43**: 5.37-5.46. An existing heating and ventilation controller was provided with an experimental humidity sensor and a new temperature-humidity control (THC) strategy. The controller regulated the ventilation system with a proportional-integral-derivative (PID) algorithm. Humidity control was achieved with a proportional control loop using the ventilation system while the heater was modulated with an on/off control. The controller was evaluated in six identical grower/finisher pig rooms for eight weeks in winter and early spring. Three rooms were provided with THC controllers while the other rooms had conventional temperature-only controllers (TC). The new THC controller provided very good control of room temperature and relative humidity (RH). In conventional rooms over the first three weeks, the time period when RH was higher than the setpoint occurred for 15 to 85% of the time and the highest RH reached 86%. In THC rooms, the controller operated under THC mode for 6 to 54% of the time and considering the maximum RH values reached (71 to 76%), this mode was very effective in maintaining the RH close to the setpoint (69 to 70%) and the setpoint plus the P-band (74 to 75%). On average, temperature control was not affected by the THC strategy implementation. However, temperature fluctuations up to 0.8˚C over 15 min were observed on some occasions in THC rooms. The oversized heater and the time parameters in the controller are likely responsible for those temperature fluctuations.

Un contrôleur de chauffage et de ventilation a été équipé d'une sonde d'humidité relative expérimentale et d'une nouvelle stratégie de contrôle de la température et de l'humidité (THC). La température était contrôlée par le contrôleur en actionnant le système de ventilation et en utilisant un algorithme proportionnel-intégral-dérivé (PID). Au sein du contrôleur, l'humidité était contrôlée par une boucle proportionnelle et le chauffage était modulé en marche/arrêté. Le contrôleur a été évalué en hiver et tôt au printemps dans six chambres de croissance-finition identiques durant huit semaines. Trois des chambres étaient équipées du contrôleur THC et les trois autres chambres étaient munies de contrôleurs conventionnels pour le contrôle de la température (TC) seulement. Le nouveau contrôleur THC a assuré un bon contrôle de la température et de l'humidité relative dans les chambres. Dans les chambres munies de contrôleurs conventionnels et durant les trois premières semaines, l'humidité relative a été supérieure à la consigne de 15 à 85% du temps et l'humidité relative maximale a été de 86%. Durant la même période et dans les chambres THC, le contrôleur a opéré en mode de contrôle de l'humidité relative de 6 à 54% du temps et en considérant les valeurs maximales d'humidité relative (71 à 76%), celui-ci a été très efficace à maintenir l'humidité relative près de la consigne (69 à 70%) et de la consigne plus la bande proportionnelle (74 à 75%). En moyenne, le contrôle de la température n'a pas été affecté par l'ajout de la stratégie THC. Cependant des fluctuations de température allant jusqu'à 0,8°C sur une période de 15 min ont parfois été observées dans les chambres THC. Le surdimensionnement de l'unité de chauffage et les paramètres de temps du contrôleur sont probablement responsables de ces fluctuations.

INTRODUCTION

Extreme high or low relative humidity (RH) is detrimental for livestock, workers, and production buildings. High RH can reduce animal performance (Parker 1968) and affect heat dissipation of animals at elevated temperatures (Esmay 1969). Moreover, moisture accumulated within the building structure can accelerate its corrosion and reduce the building longevity (Holmberg 1972; Gratwich 1975; Zhang 1994). On the other hand, low RH can lead to respiratory disorders and high dust levels (MWPS 1983).

Relative humidity is also generally used as an indicator of the air quality in the building and it is assumed that proper humidity control will also provide acceptable gas concentrations. Therefore, humidity control has long been recognized as one of the most important approaches to improve the environment of livestock buildings. However, due to the corrosive environment of livestock facilities, the accuracy of humidity sensors is affected to varying degrees and they can even fail after a relatively short barn exposure (Erdebil and Leonard 1989; Hao and Leonard 1994; Lemay et al. 1998). Consequently, incorporation of RH data into the environmental control strategy for livestock buildings is limited by the availability of RH sensors which are economical and reliable, require low maintenance, and provide an easy interface with automatic controllers. Hence, humidity control has not been widely implemented and the majority of current animal-production facilities use temperature-only control (TC) strategy.

The TC strategy cannot directly control the RH and other contaminants in the building. Instead, humidity control is indirectly achieved through a manual setting of the minimum ventilation rate (MVR) based on theoretical requirements or observations on barn air conditions. Since the MVR required for moisture control changes with various factors such as ambient weather conditions, temperature setpoint, animal type and size, management, and building characteristics, to set the MVR manually to provide the best compromise consistently between expensive over-heating and unhealthy under-ventilation is a difficult and tedious task (Zhang 1993). Most barn operators are unable to maintain a proper MVR and the buildings are either over ventilated with high heating cost or under ventilated with high humidity and poor air quality. For example, on the Canadian Prairies, high humidity levels are encountered for nearly two-thirds of the year when the outside temperature is below the heat deficit temperature (Zhang and Barber 1993).

A computer simulation showed that a temperature-humidity control (THC) strategy provided the best thermal response and used the least supplemental heat compared with TC strategies (Zhang and Barber 1995). In this case, the heater was controlled by a humidistat(s) and fans were controlled by a thermostat(s). It also demonstrated that oversized heating/ventilating equipment had little effect on this THC system while it resulted in inadequate thermal response and higher energy consumption for TC systems.

Vansteelant et al. (1988) developed a computer-based humidity/temperature controller for a swine farrowing facility and tested its performance under spring-fall weather conditions. The controller used a humidistat to control the ventilation system and two models (building and animal response) to predict the required ventilation rate and supplemental heat to achieve moisture and sensible heat balances. This controller was reported to be effective for controlling RH, but a safety system was suggested considering that the control system failed and was forced to be shut down several times due to hardware problems. The controller performance was not studied for outside temperatures below 0^{o}C and above 15^{o}C. A conventional temperature-based fan controller was modified to modulate fan speed on the basis of RH (Hao and Leonard 1995). This controller was tested in two rooms in a turkey barn for six weeks and the RH setpoints were 30 and 60%. These two rooms were equipped with a separate temperature control system. The controller performed better at the low RH setpoint.

Several commercially available THC controllers, manufactured by Fancom (Fancom, Panningen, The Nederlands), Hotraco (Hotraco BV, Horst, The Nederlands), Monitrol (Montréal, Québec), and Raydot (Cokato, Minnesota), include the RH control feature. The RH control is generally achieved by increasing the MVR to control humidity. For the SKOV DOL 34H controller (SKOV A/S Hedelund 4, Glyngore, Denmark), a humidistat can control either the heater or the ventilation system. When the heater is controlled by RH input, the humidistat activates the heater, room temperature increases, and the ventilation system responds to this temperature rise to remove moisture from the room.

There is not a lot of information on the performance of these THC controllers. Zhang (1993) conducted an experiment in a broiler chicken barn with a one-phase climate controller (DOL-30H, SKOV A/S Hedelund 4, Glyngore, Denmark). The RH was controlled by increasing supplemental heat. However, this strategy was only useful during the heating season. During hot humid weather when the ventilation system reached its maximum capacity, supplemental heat was still required for humidity control. The system did not have the ability to maintain both temperature and RH at their setpoints during mild weather. An ideal controller using this control strategy should give priority to temperature control and should shut off the heater during mild humid weather.

Lemay et al. (1998) evaluated two TDK RH sensors (TDK Corporation of America, Mount Prospect, IL) with different combinations of coating and filter treatments. With the best treatment combination and after a one year exposure in a pig barn, the average accuracy of the sensor went from an initial value of ±5 to ±8%. Simulations completed by Lambert et al. (1999) indicated that the optimum THC strategy in a grower-finisher pig building was proportional (P) control of the RH by the ventilation system with a RH setpoint of 75% and a 5% proportional band (P-band).

The objective of this study was to integrate the modified TDK RH sensor (Lemay et al. 1998) and the optimized THC strategy (Lambert et al. 1999) in an existing heating and ventilation controller and to evaluate the performance of the new THC controller under commercial barn conditions. The initial hypotheses were that the new THC controller would operate reliably without any intervention, would maintain temperature and RH setpoints, would improve the average air quality in the building by reducing carbon dioxide (CO_2) and ammonia (NH_3) concentrations, would minimize supplemental heat consumption, and would maintain pig performance.

MATERIALS and METHODS

The RH sensor, the THC strategy and the controller

The RH sensor used with the THC controller was the TDK CHS-UGS RH sensor (TDK Corporation of America, Mount Prospect, IL) with a protective coating and a TDK experimental filter. The electronic portion of the sensor was sprayed with a pure silicone conformal coating. This type of sensor was evaluated for one year in a commercial grower/finisher swine building without any maintenance providing an accuracy of ±4.9% after six months and of ±8.0% after one year (Lemay et al. 1998). Its performance was equivalent to other more expensive commercial RH sensors tested with the same procedure.

Considering the observations made with the computer model (Lambert et al. 1999), the new THC controller was expected to control both room temperature and RH at setpoint values - for winter conditions with a RH setpoint of 75% and a P-band of 5%. Even if the TDK RH sensor showed promising performance, the THC controller needed to be protected from a false sensor reading. As has been done for some commercial controllers, the humidity control was only allowed to control the first stage fan within a lower (LLMVR) and an upper limit (ULMVR) of its ventilation rate. The LLMVR ensures a minimum ventilation rate in the room even if the RH is lower than the setpoint. On the other hand, the ventilation rate for THC cannot exceed ULMVR which prevents energy wastage. Wastage can be associated with excessive ventilation rates and the associated heating requirements if the RH sensor reads too high a RH level or when the outside air coming in is relatively warm but very humid.

The relationships developed by Lambert et al. (1999) between inside RH and THC control strategies (shown in

Table 1. Relationship between inside relative humidity and temperature and humidity control (THC) strategies in the model suggested by Lambert et al. (1999).

Type of THC control	RH input*#	Ventilation rate (VR) output
Proportional (P)	$W < W_{sp}$	$VR = LLMVR$
	$W_{sp} < W < W + \Delta W$	$VR = LLMVR + \frac{(W - W_{sp}) * (ULMVR - LLMVR)}{\Delta W}$
	$W > W + \Delta W$	$VR = ULMVR$ then *TC*
Proportional-Integral-Derivative (PID)	$W < W_{sp}$	$VR = LLMVR$
	$W_{sp} = W$	$LLMVR < VR < ULMVR$
	$W > W_{sp}$	$VR = ULMVR$ then *TC*

* RH is converted to the absolute humidity ratio (W) to insure stability of the algorithm.
\# W_{sp} = absolute humidity ratio setpoint; ΔW = humidity ratio proportional band of the controller.

Table 1) provide the control conditions for the THC strategy with an emphasis on the THC mode. These relationships developed for the computer model were directly implemented in the controller. Therefore, the controller gives priority to temperature control (TC) and THC occurs within the limits of stage-1 ventilation.

The TDK RH sensor and the THC strategy were implemented in the "Rapid Control" controller of Delair Systems Ltd. (Humbolt, SK) by Critical Control (Saskatoon, SK). The regular "Rapid" controller included PID control of the ventilation system for TC while the heater was provided with On/Off control. The user could specify the room temperature setpoint and the minimum ventilation rate. Both parameters could be fixed or be progressively modified based on a specified time period. It could also control different events such as light, water, feed schedules, etc. Each controller was able to control two rooms independently. In the THC mode with the experimental THC Rapid controller, it was necessary to define the room temperature and RH setpoints, the RH P-band, and the values of LLMVR and ULMVR.

Temperature and RH were read every 8 s, but the ventilation rate was updated every minute considering that it took a longer time for humidity to stabilize. For the regular Rapid controller, the sampling time was 5 s. The whole system (temperature, RH, fan and heater operating conditions, lights, etc.) was monitored through an interface with a Windows 95 program, which was custom-written for this project.

The THC controller evaluation

The evaluation of room air quality obtained with the experimental THC controller was conducted over eight weeks from February to April 1999 at Prairie Swine Centre Inc. (PSCI), Saskatoon, SK. Six identical grower/finisher rooms (5.3 m × 14.3 m) formed three pairs of experimental units, i.e. rooms 1 TC and THC, rooms 2 TC and THC, and rooms 3 TC and THC. All East rooms of each pair were defined as TC rooms and provided with regular Rapid controllers (1-TC, 2-TC, 3-TC) while all West rooms of each pair were THC rooms equipped with modified THC Rapid controllers (1-THC, 2-THC, 3-THC). All six rooms were next to each other on the east-west direction and considered exposed to similar ambient conditions with one north exterior wall per room, one south wall facing the common hallway, and identical dividing walls separating the rooms. Each room contained six pens and 68 pigs in total: three pens for barrows and three others for gilts. Pigs were fed PSCI regular diets during the growing-finishing period with automatic feeding systems.

All the rooms were equipped with the same heating and ventilation systems. Each room had an 18 kW natural gas heater (ATL-1200, L-B White, La Crosse, WI) controlled with an on/off switch. There were three fans in each room: stage-1 and stage-2 fans being variable speed propeller fans (NW1200 and NW2K, respectively, Delair Systems Ltd., Humbolt, SK) and the stage-3 fan being a single speed fan. During the whole experimental period, all the stage-3 fans were not required and were disabled and sealed. Each room was equipped with six identical air inlets.

Limited by the number of pigs available on a weekly basis at PSCI, the rooms were filled in pairs (one control and one treatment). Rooms started successively on February 15 (rooms 1 TC and THC, initial pig mass 32 kg), February 19 (rooms 2 TC and THC, initial pig mass 23 kg) and February 26 (rooms 3 TC and THC, initial pig mass 21 kg). Pig ages and masses in each pair of rooms were made very similar by randomized allocation of pigs to rooms.

Control settings for experimental rooms

All the controller settings for TC and THC rooms, such as temperature setpoints, light schedule, etc., were the same, except that THC rooms used THC functions. The temperature control band for the heater was set at 0.2°C and the heater was be turned on if the room temperature was 0.2°C lower than the setpoint. For fans, the switch band was 0.7°C and the switch time was 10 s, which means that when the room temperature was above the setpoint temperature by 0.7°C for 10 s, the fans would switch to cooling mode. The fans would then stay into the cooling mode as long as the temperature would fall below the temperature setpoint minus the control band. The proportional constant was 0.14 and the integral time was 600 s. Since there might have existed some noise and there was no filter in place, the derivative time was set at 0 s, which meant the controller actually only used proportional and integral functions. The temperature sensor and the TDK RH sensor for the controller were located at the centre of the rooms 1.6 m above the floor together with the other sensors for air monitoring.

The temperature setpoint was 21°C for 25 kg pigs and was reduced gradually over 94 days to 15°C when pigs were 100 kg. Lights were on from 0700 to 1900h in all rooms. As the experiment could only start late in February, in THC rooms the RH setpoint was set at 70% with a 5% P-band, instead of 75%, to increase the number of days requiring humidity control. The minimum rotation speed for stage-1 fans was 25% of full speed as they could not run at a lower speed in experimental rooms. According to calculations for 25 kg pigs in experimental rooms, LLMVR and ULMVR were set at 25% and 100% of full speed of the stage-1 fans, providing a ventilation rate of approximately 0.12 and 0.57 m^3/s, respectively. For TC rooms, the speed of stage-1 fans for the MVR was fixed at 30% of full speed (approximately 0.14 m^3/s) for the first week and 26% (approximately 0.12 m^3/s) thereafter . These ventilation rates were in agreement with calculations to maintain 70% RH at the design temperature for Saskatoon (-37°C) with 25 kg pigs.

Data collection

Controller performance and its influence on room temperature, RH, heating requirements, and the subsequent impact on pigs were monitored. Carbon dioxide (CO_2), ammonia (NH_3), and dust mass concentrations were also measured. In each room, RH was measured with a bulk polymer humidity sensor (model RH2I-R, General Eastern Instruments, Watertown, MA, accuracy: ±2%). Room and air inlet temperatures were monitored with type T thermocouples (accuracy: ±0.5°C). The RH sensor and thermocouple for room air monitoring were placed at the centre of the room 1.6 m above the floor. The thermocouple for inlet temperature monitoring was installed at the centre of the air inlet. The ventilation rate was calculated from the static pressure difference across the fan and the fan rotation speed. Static pressure was measured with static pressure transducers (Model 264, Setra Systems, Toronto, ON). Proximity sensors (model SR3, Microswitch, Freeport, IL) monitored fan rotation speed. Natural gas consumption was monitored with a diaphragm gas meter (Model AC250 T.C Diaphragm Gas Meter, Canadian Meter, Edmonton, AB). The outside RH and temperature were measured with an integrated sensor (model MRHT-3, General Eastern Instruments, Watertown, MA, RH accuracy: ±3%, temperature accuracy: ±0.5°C). All the above data were sampled every minute with 15 min averages recorded by three data loggers (Datataker DT 100, Data Electronics (Aust.) Pty. Ltd., Rowville, Australia).

The General Eastern (GE) humidity sensors and TDK humidity sensors were calibrated prior and post in-barn trial in the laboratory against a chilled mirror dew-point hygrometer (Model Dew-10, General Eastern Instruments, Watertown, MA, accuracy ±0.5°C). The equipment and procedure for static humidity sensor calibration suggested by Lemay et al. (1998) were used. By calibrating the chilled mirror hygrometer against five saturated salt solutions (lithium chloride [11.3% RH], potassium acetate [23.1% RH], magnesium chloride [33.1% RH], sodium chloride [75.4% RH] and barium chloride [90.0% RH]), the accuracy of the calibration setup was found to be within ±3% RH.

Pigs were weighed at the beginning, after four weeks, and at the end of the experiment. Pig average daily gain in each period was calculated.

Ventilation rate calculations

The ventilation rate was calculated from the static pressure difference across the fan and the fan rotation speed using Eq. 1 (Barber et al. 1988). Table 2 gives the coefficients for stage-1 and stage-2 fans in the variable speed range.

$$Q = \left(b + cH^{n_1}\right)N^{n_2} \times 10^{-3} \qquad (1)$$

where:

Q = fan airflow rate (m^3/s),
b = experimental coefficient,
c = static pressure coefficient,
H = static pressure head across the fan (Pa),
n_1 = exponential coefficient of static pressure,
N = fan speed (rpm), and
n_2 = exponential coefficient of fan speed.

RESULTS

Deviations from the protocol

Different experimental problems occurred during the controller evaluation and these affected the accuracy of the measurements over some periods. First of all, the TDK RH sensor had a loose connection in room 1-THC from February 28 to March 2. The computer lost control of fans and heaters in some rooms several times and controllers had to be restarted. Manure pits were also flushed with a different schedule in some rooms over the course of the experiment. These factors resulted in heating and ventilation loads being different between rooms at given times.

Furthermore, after all stage-2 fans were enabled on March 18, the data logger started to give faulty readings from time to time for all proximity sensors, and especially for stage-2 fans. This malfunction was principally associated with an electronic component within the proximity

Table 2. Specifications and coefficients for stage-1 (NW1200) and stage-2 (NW2K) fans.

Fan	Diameter (m)	Flow rate at 31 Pa (m^3/s)	Coefficients for ventilation rate calculations (n.u.)			
			b	c	n_1	n_2
NW1200	0.306	0.566	8.28×10^{-4}	-5.1×10^{-6}	1.1237	1.8423
NW2K	0.406	0.960	5.52×10^{-3}	-7.6×10^{-6}	1.2467	1.6449

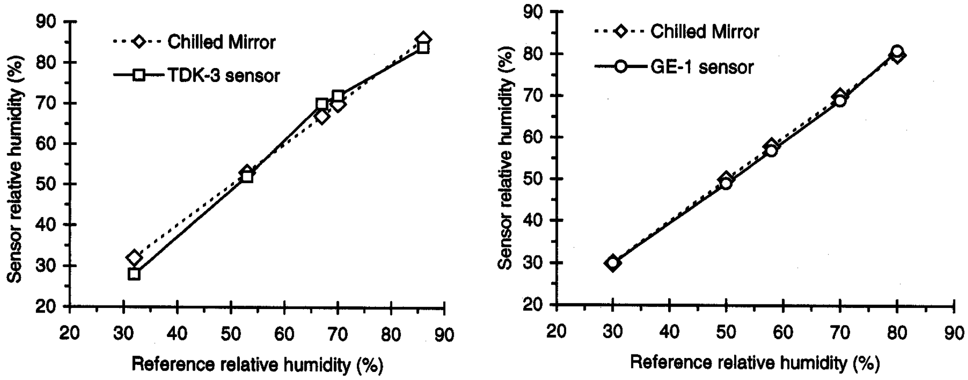

Fig. 1. Humidity sensor calibration results after an eight-week in-barn exposure.

sensor circuit. Electronic noise that was completely random made the data analysis process very difficult. As a result, it was not possible to compare the average ventilation rate for each room on a weekly basis. However, the ventilation rate could still be compared over specific periods when a pair of rooms were under similar conditions and when the monitoring system worked properly. Further, the average values over the experimental period for NH_3 and CO_2 concentrations and the dust mass concentration could not be compared for all rooms but could be compared for each pair of rooms.

Some power supplies for pressure transducers failed during the experiment and static pressure data were lost for those days. When the static pressure value was not available, the fan rotation speed was used to represent the ventilation rate.

All rooms were provided with an identical natural gas heater but the energy efficiency of each individual heater was unknown. It was assumed that this efficiency would be similar from one heater to another, but gas consumption measurements obtained later under similar conditions did not support this assumption. Consequently, gas consumption values need to be analyzed with caution.

Accuracy drift of RH sensors

No adjustments were performed on any of the RH sensors during the experiment. TDK CHS-UGS RH sensors had an accuracy ranging from -2.5 to -3.1% (reading low) before the experiment. After eight weeks in the barn, their accuracy varied from ±1.9 to ±2.0%. This accuracy drift of the TDK CHS-UGS sensor was very consistent with what was found by Lemay et al. (1998). The humidity monitoring sensors, i.e., GE sensors, also showed slight accuracy drifts. Their accuracy ranged from ±1.1 to ±3.2%. All the sensor readings were linearly corrected according to initial and final calibration results. Figure 1 presents the sensor performance in the final calibration.

Performance of the THC controller

From the beginning of the experiment until March 18, only the stage-1 fan was working in all rooms. The stage-2 fan was enabled in the afternoon of March 18, as the inlet temperature had increased significantly, and from this date, the controller was mainly operating in TC mode. During that period, when RH control was needed, THC provided this control consistently.

Figures 2 to 5 describe the THC controller operation for two periods of 72 h in room pair 2 under winter conditions. Based on these figures, the controller was very effective in controlling temperature and RH in experimental rooms for different combinations of moisture production and weather conditions. For example, Figs. 2 and 3 present the inlet temperature, the room temperature, RH, and fan rotation speed in room pair 2 from February 20 to 23. These graphs clearly show that around 1200h over those three days, the RH in the TC room rose to around 75%. For the same period in the THC room, the THC

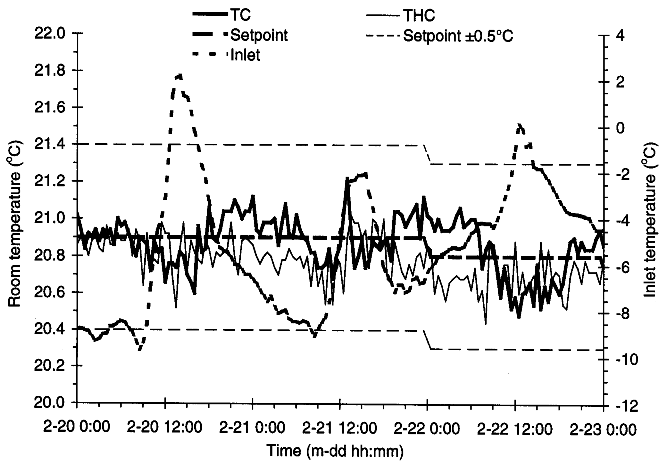

Fig. 2. Room and inlet air temperature in the room pair 2 for TC and THC February 20-23, 1999.

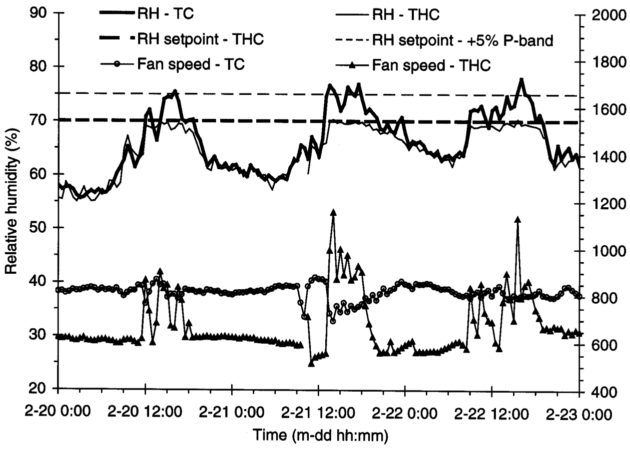

Fig. 3. Relative humidity and stage-1 fan rotation speed in room pair 2 for TC and THC February 20-23, 1999.

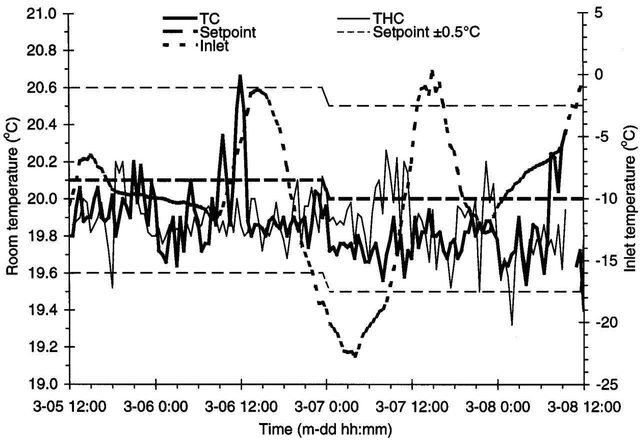

Fig. 4. **Room and air inlet temperatures in the room pair 2 for TC and THC March 5-8, 1999.**

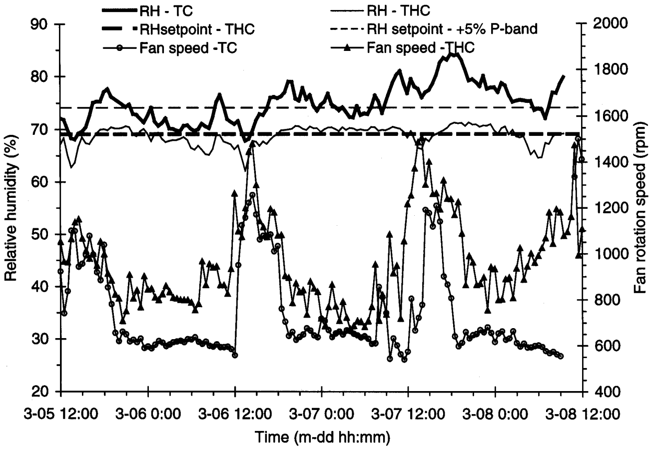

Fig. 5. **Relative humidity and stage-1 fan rotation speed in room pair 2 for TC and THC March 5-8, 1999.**

controller increased the stage-1 fan speed to maintain the RH at the setpoint and below the setpoint plus the P-band. The THC system was therefore able to react to different levels of moisture production in the room and to control the RH at the setpoint level. It is also interesting to note from Fig. 3 that the highest moisture production occurred from 1200h to 1800h and was likely associated with an increased pig activity (Pedersen and Takai 1997). Humidity control was mostly operating during daytime, while at night RH fell below the setpoint which indicated that the LLMVR was higher than humidity control requirements.

The same kind of response of the THC controller can be observed in Figs. 4 and 5 for three different days. The controller managed to keep the RH at the setpoint or below the setpoint plus the P-band in the THC room while the RH reached 85% on one day in the TC room. The outside temperature went down to -23°C at 0300h on March 7. In Fig. 6, the natural gas consumption measurements illustrate the heater response to this cold temperature.

After the stage-2 fan was enabled, the room temperature was still kept around the setpoint (Fig. 7). As shown in Fig. 8, when

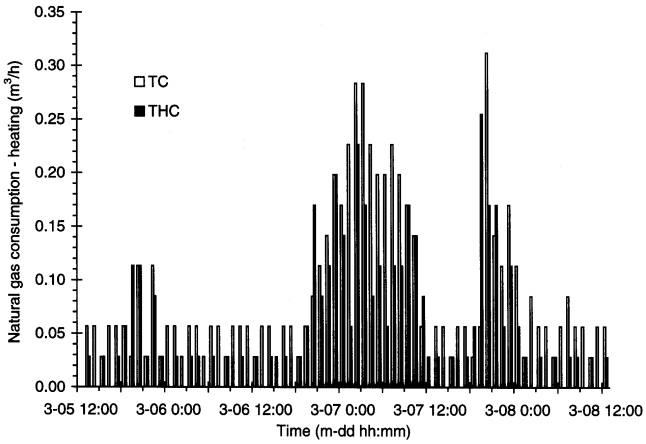

Fig. 6. **Gas consumption in room pair 2 for TC and THC March 5-8, 1999.**

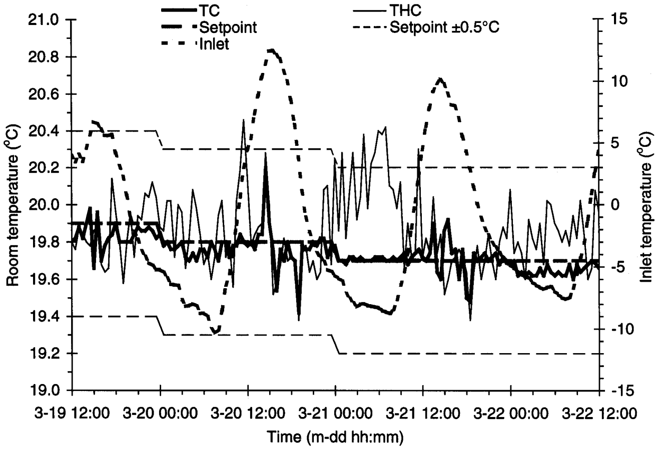

Fig. 7. **Room and inlet air temperatures in the room pair 3 for TC and THC March 19-22, 1999.**

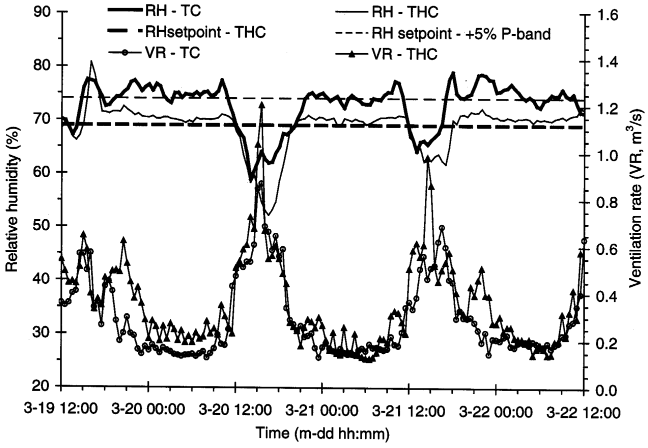

Fig. 8. **Relative humidity and ventilation rate in room pair 3 for TC and THC March 19-22, 1999.**

Table 3. Average room temperature and differences with temperature setpoints over the eight-week period.

Week[1]	Room pair	Temperature (°C)				
		Inlet	TC	THC	ΔT_{TC}[2]	ΔT_{THC}[2]
1	1	-7.4	19.8	18.8	0.0	0.0
	2	-4.9	20.8	20.8	0.2	0.2
	3	-8.6	21.0	N/A	0.1	N/A
2	1	-4.2	19.4	18.3	0.3	0.2
	2	-8.2	20.3	19.9	0.2	0.3
	3	-7.0	20.8	20.8	0.2	0.2
3	1	-11.1	19.1	17.8	0.1	0.2
	2	-7.6	19.8	19.5	0.3	0.2
	3[3]	-2.2	20.1	20.3	0.1	0.2
4	1	-4.0	19.0	18.5	0.6	0.3
	2[3]	-2.0	19.1	19.4	0.4	0.3
	3	-0.1	19.6	19.8	0.1	0.2
5	1[4]	-1.0	18.6	18.6	0.5	N/A
	2	0.1	18.7	18.9	0.4	0.1
	3	1.5	19.3	19.2	0.1	0.1
6	1	1.9	17.8	17.4	0.2	0.1
	2	1.8	18.3	18.5	0.4	0.2
	3	2.9	19.1	18.6	0.3	0.5
7	1	0.4	17.3	17.3	0.2	0.3
	2	3.2	18.3	18.4	0.7	0.5
	3	4.9	18.5	18.3	0.3	0.3
8	1	5.3	17.8	17.7	1.1	1.1
	2	5.2	17.6	17.7	0.6	0.4
	3	7.1	18.6	18.4	0.8	0.7
Average[5] (stage-1 fan only)	1	-6.7			0.3	0.2
	2	-5.7			0.3	0.3
	3	-7.8			0.2	0.2
Average (8 weeks)	1				0.8	0.8
	2				0.4	0.3
	3				0.3	0.3

[1] The same week number was not the same time for each pair of rooms depending on starting date.

[2] ΔT: temperature difference between the room amd the setpoint.

[3] Stage-2 fans were enabled on the last day of this week.

[4] Stage-2 fans were enabled on the third day of this week.

[5] With only the stage-1 fans working before March 18, 1999; after that time, stage-2 fans were enabled.

the inlet temperature was low enough and the stage-2 fan stopped, the controller went back to THC mode and kept the RH at the required level. During the humidity control period, the ventilation rate in the THC room was higher than in the TC room (Fig. 8). However, as the stage-3 fans were disabled for the whole experiment, when the inlet temperature became so high that the required ventilation rate exceeded the total capacity of stage-1 and -2 fans, room temperature increased higher than the setpoint. The warmer outside conditions allowed us to verify that no stability problems were observed with the controller going back and forth from TC to THC mode on a daily basis.

Average temperature and RH in experimental rooms

As shown in Table 3, the controller provided good temperature control in both TC and THC rooms. The average difference between the room temperature and the setpoint increased from 0.1 to 1.1˚C over the course of the experiment. The maximum difference (1.1˚C) was observed during the last week in rooms 1-TC and 1-THC when ventilation requirements exceeded the fans' capacity. Therefore, the THC strategy implementation did not compromise the controller capabilities of controlling temperature.

The RH in TC rooms varied substantially on a daily basis (Figs. 3, 5, and 8). It was very rare that the MVR just happened to be at the right level to maintain the room RH around 70%. Most of the time, the RH was either higher or lower than the desired level. When the inlet temperature was low, the controller in TC rooms maintained its constant MVR, and a high RH was observed. This was a typical pattern during daytime that can be observed in all of Figs. 3, 5, and 8. On the other hand, when the MVR setting in TC rooms was higher than required by humidity control, the RH was low.

Table 4 shows average RH in all rooms for the entire experimental period. In THC rooms, the weekly average RH was kept below the setpoint throughout the whole experiment while the average RH was sometimes higher than the RH setpoint in TC rooms. An average RH exceeding the setpoint was observed over weeks 3, 4, and 5 of the experiment in rooms 2-TC and 3-TC. The controller in THC rooms was therefore capable of decreasing the average RH maintained in those rooms. The average RH was very similar in TC and THC rooms during the last three weeks of the experiment. The lack of large differences in average RH between TC and THC rooms is primarily due to the late starting date and mild weather conditions during the experiment.

To compare RH conditions with the TC and THC controller, Table 5 gives maximum and minimum RH values, the daily time period when the RH in TC and THC rooms was higher than the RH setpoint and the average RH observed during that time period. For THC rooms, this time period also corresponds to when the controller worked under THC mode. Since room 1-THC experienced more problems than the other rooms (the computer lost control for a total of four days from weeks 1 to 3), Table 5 only presents the results for weeks 1 to 3 and for room pairs 2 and 3. In TC rooms, the RH was higher than the RH setpoint for 15 to 85% of the time and the highest RH measured reached 86%. In THC rooms, the controller operated under THC mode for 6 to 54% of the time. Considering the maximum RH values (71 to 76%), it was very effective in maintaining the RH close to the setpoint (69 to 70%) and the setpoint plus the P-band (74 to 75%).

Average CO_2, NH_3, and dust concentrations

Table 6 gives average CO_2 and NH_3 concentrations, and dust mass concentration over the experimental period. The THC

Table 4. Average room relative humidity (RH) and differences with RH setpoints over the eight-week period.

Week[1]	Room pair	RH (%)					
		Outside	TC	$THC_{Setpoint}$[2]	THC	ΔRH_{TC}[3]	ΔRH_{THC}[3]
1	1	N/A	65	70	69	-5	-1
	2	N/A	66	70	65	-4	-5
	3	N/A	63	70	63	-7	-7
2	1	N/A	62	70	61	-8	-9
	2	N/A	69	70	68	-1	-2
	3	79	69	70	66	-1	-4
3	1	79	65	69	63	-4	-6
	2	79	73	69	68	4	-1
	3[4]	68	70	69	67	1	-2
4	1	76	61	69	63	-8	-6
	2[4]	68	76	69	61	7	-8
	3	63	67	69	67	-2	-2
5	1[5]	64	58	69	62	-11	-7
	2	63	73	68	60	5	-8
	3	59	58	68	58	-10	-10
6	1	60	57	68	62	-11	-7
	2	59	66	68	57	-2	-11
	3	56	53	68	54	-15	-14
7	1	61	54	68	60	-14	-8
	2	56	59	67	55	-8	-12
	3	45	50	67	52	-17	-15
8	1	50	53	68	59	-15	-9
	2	45	59	67	53	-8	-14
	3	43	49	67	52	-18	-15
Average[6] (stage-1 fan)	1					-7	-6
	2					2	-3
	3					-4	-5
Average (8 weeks)	1					-10	-7
	2					-1	-7
	3					-9	-8

[1] The same week number was not the same time for each pair of rooms depending on starting date.

[2] The variation of the current RH setpoint from 70 to 67% is due to the TDK RH sensor accuracy drift. The RH setpoint was corrected with initial and final RH sensor calibration.

[3] ΔRH: RH difference between the room amd the setpoint of the paired THC room.

[4] Stage-2 fans were enabled on the last day of this week.

[5] Stage-2 fans were enabled on the third day of this week.

[6] With only the stage-1 fans working before March 18, 1999; after that time, stage-2 fans were enabled.

controller had little influence on NH_3 concentration and dust mass concentration compared with the TC strategy. However, most of the time TC rooms had lower CO_2 concentrations than THC rooms, especially in the early stage of the study when the inlet temperature was low. Considering that the moisture production level should be very similar due to the same pig number and weight, feed, and manure management in each pair of rooms, the results mean that weekly average ventilation rate in TC rooms was higher than in THC rooms. The highest CO_2 concentration in THC room was 3200 ppm which was acceptable for grower-finisher pig buildings.

Pig performance

Table 6 also shows the average daily mass gain (ADG) of pigs. The first four weeks constituted the period where THC mode was more often activated, but the ADG of pigs was very close and not statistically different in each pair of rooms (P>0.05). The last four weeks showed a trend toward ADG increase in two THC rooms compared to respective TC rooms. However, during this period, THC mode was only effective over short periods of time therefore differences in ADG increase cannot be explained strictly by controller difference. The data suggested that THC had no influence on pig performance.

DISCUSSION

Monitored results indicated that the THC controller was able to control temperature and RH adequately under various weather conditions. However, temperature fluctuations up to 0.8˚C in 15 min were frequently observed during and after the humidity control process (Figs. 4 and 7) and those fluctuations were higher than what was observed in TC rooms.

The heater size and control seems to have a marked effect on the temperature pattern stability. To control room RH, sometimes the controller had to switch frequently between TC and THC modes (Figs. 3, 5, and 8). When the controller switched from TC mode to THC mode, a higher ventilation rate was provided. Meanwhile, temperature went down until the heater dead band (-0.2ºC) was reached, and then the heater was turned on and the temperature rose again. Since the heater was oversized for the room, sometimes the temperature peaked at 0.4 to 0.8ºC higher than the setpoint due to the heater oversize and the system time delay. By that time, the RH had already decreased and the controller switched back to TC mode. Since the temperature was already higher than the setpoint, the PID controller increased the ventilation rate based on the

Table 5. High relative humidity (RH) conditions in a cold weather period (only stage-1 fan enabled).

Week[1]	Room	Relative humidity (%)			Time period when $RH \geq RH_{setpoint}$		
		Setpoint[2]	Maximum	Minimum	Cumulative time		Average RH
					(h:min/day)	(% of 24 h)	(%)
1	2 - TC	–	79	56	7:13	30.1	73
	2 - THC	70	72	55	4:07	17.1	70
	3 - TC	–	77	51	3:32	14.7	73
	3 - THC	70	71	54	1:34	6.5	71
2	2 - TC	–	86	59	10:29	43.7	73
	2 - THC	70	76	61	8:11	34.1	71
	3 - TC	–	78	57	10:51	45.2	72
	3 - THC	70	74	55	4:09	17.3	70
3	2 - TC	–	84	62	20:25	85.0	74
	2 - THC	69	75	59	12:50	53.5	71
	3 - TC	–	80	54	14:58	62.3	72
	3 - THC	69	73	56	10:11	42.5	70

[1] The same week number was not the same time for each pair of rooms depending on starting date.

[2] The variation of the current RH setpoint from 70 to 67% is due to the TDK RH sensor accuracy drift. The RH setpoint was corrected with initial and final RH sensor calibration.

temperature difference between the room and the setpoint. This ventilation rate required by TC reduced the temperature very rapidly. This process was typical in cold weather.

To reduce temperature fluctuations, it is important to properly size the heater if overshooting occurs or to control it with a P control strategy. Such a control strategy would reduce the impact of the heater capacity. Interestingly, this observation contradicts what was found by Zhang and Barber (1995) regarding the impact of heater size on thermal response and energy consumption with a THC strategy.

Controller time settings used in the experiment have certainly influenced the dynamic response of the controller. A different setting of P and PID time parameters in the controller may provide better stability of the temperature profile under the THC mode. Since experimental data were recorded every 15 min, 112 sampling periods for the controller (sampling every 8 s) and 15 control mode switches (updating every 1 min) had been done during the data collection period. Thus, room temperature and RH conditions changed more rapidly than the data collected, and the recorded data could not fully reflect the actual fluctuation of monitored parameters. To describe and understand the controller dynamic behaviour, all measurements should be recorded over a shorter time interval (ex.: 30 s or 1 min). More investigations will be required to describe appropriately the dynamic response of the THC controller.

Table 6. Average carbon dioxide (CO_2), ammonia (NH_3), and dust mass concentration (DMC), and pig average daily gain (ADG) during the eight-week period.

Parameter	Weeks	Room pair 1		Room pair 2		Room pair 3	
		TC	THC	TC	THC	TC	THC
CO_2 (ppm)	1 to 4	1513	2463	1500	2350	1833*	2567*
	Average	1321	1943	1300	1893	1321	1636
NH_3 (ppm)	1 to 4	10.9	10.3	8.6	10.0	13.7	11.8
	Average	8.8	8.6	8.1	8.5	8.5	7.4
DMC (mg/m^3)	1 to 4	5.59	5.92	4.82	4.95	4.38	4.17
	Average	4.88	4.93	4.33	4.91	3.65	3.53
ADG (kg/d)	1 to 4	0.824	0.819	0.757	0.762	0.675*	0.671*
	5 to 8	0.817	0.861	0.887	0.894	0.799	0.852
	Average	0.821	0.840	0.822	0.828	0.737	0.762

* Weeks 1 to 3 for room pair 3.

Apparently, the LLMVR of the stage-1 fan in THC rooms was too high for efficient humidity control. The fan was unable to maintain a stable flow rate with a low rotation speed and a slight change in static pressure was sufficient to stop the fan. This resulted in higher ventilation at night in cold weather in THC rooms and consequently the heat consumption was higher than it should have been. This observation suggests that when a THC strategy is implemented in a grower-finisher room, the first stage fan needs to have an effectively larger flow rate range or it needs to be capable of providing a lower flow rate compared to a conventional ventilation system design. Using a smaller fan or a damper control working in combination with fan speed control may be the most appropriate strategies for cold climate buildings.

Simulation results showed that a 75% RH setpoint with THC control would require less energy compared to a TC control when the MVR is set to maintain 70% RH at design conditions (Lambert et al. 1999). Due to the late starting time of the experiment and warmer ambient conditions, the RH setpoint for THC rooms was set at 70% instead of 75% to force the controller to operate in humidity control mode more frequently. Therefore, simulation results obtained by Lambert et al. (1999) have not been validated during the current experiment. These authors also showed that a 70% RH setpoint using THC control would require more supplemental heat than TC control when the MVR is set to maintain 70% RH at design conditions. However, due to some problems with natural gas consumption measurements and unknown natural gas heater efficiencies, the current study was unable to verify those calculations. Further experiment is needed to test the simulation results by Lambert et al. (1999) and the energy consumptions using THC and TC strategies.

CONCLUSIONS

An existing controller was provided with an experimental humidity sensor and a new THC strategy. The controller regulated the temperature with the ventilation system and a PID algorithm. The THC was achieved with a P control loop using the ventilation system while the heater was modulated with an on/off control.

The new THC controller provided very good control of room temperature and RH. For three weeks in TC rooms, the time period when RH was higher than the setpoint occurred for 15 to 85% of the time and the highest RH reached 86%. In THC rooms, the controller operated under THC mode for 6 to 54% of the time and considering the maximum RH values (71 to 76%), it was very effective in maintaining the RH close to the setpoint (69 to 70%) and the setpoint plus the P-band (74 to 75%).

On average, temperature control was not affected by the THC strategy implementation. However, temperature fluctuations up to 0.8°C over 15 min were observed on some occasions in THC rooms. The oversized heater and the setting of time parameters were likely responsible for those temperature fluctuations and more investigations are required to completely test this hypothesis.

Comparing THC and TC rooms, NH_3 and dust mass concentrations were not affected. The CO_2 concentration was generally higher in THC rooms indicating a lower average ventilation rate. Pig performance was not affected by control strategies.

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