CLIMATE CONTROL BASED ON TEMPERATURE MEASUREMENT IN THE ANIMAL−OCCUPIED ZONE OF A PIG ROOM WITH GROUND CHANNEL VENTILATION

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ABSTRACT. *It is known that there can be a significant temperature difference between the position of the climate controller sensor (room temperature) and the animal−occupied zone (AOZ) in a pig room. This study explores the advantages of using AOZ temperature in climate control. The objectives were: (1) to evaluate a current climate control system in a practical room with ground channel ventilation for weaned piglets by comparing AOZ and room temperature, and (2) to determine advantages of control of the heating system based on AOZ temperature by a model−based predictive (MBP) controller. Comparison of AOZ and room temperature showed that during the first 10 days of the two experimental batches, AOZ temperature was lower and showed greater fluctuations than room temperature, most likely due to the switching of the heating system (on/off). Animals close to the sensor could disturb the AOZ measurement. This was not the case during colder nights, when animals moved away from the sensor and the measured AOZ temperature was a good indicator of the air temperature around the animals. The data for those periods were suitable for use in this climate control study, but when applying the system in practice the disturbing effect needs to be prevented by better protection of the AOZ sensor. For the second objective, the course of the AOZ temperature was modeled based on data for five nights when the heating switched on and off several times (goodness of fit $R_t^{\,2} = 0.77$). One of the models was integrated in a simulated MBP controller that uses the model to predict future AOZ temperature; the controller switches the heating system on before the AOZ gets too cold and off before it gets too warm. The simulated AOZ temperature was more stable during an 11 h cold period; the standard deviation was reduced from 0.44°C to 0.18°C.*

Keywords. *Controlling, Ground channel ventilation, Microclimate, Model−based predictive control, Pig housing, Ventilation.*

In a pig room, the climate in the animal−occupied zone (AOZ) is of main concern (Randall, 1980; Hoff, 1995; Zhang et al., 2001; Van Wagenberg and Smolders, 2003). Significant temperature differences can occur between the sensor position for climate control and the AOZ (Randall, 1980; Van 't Klooster, 1994; Van Wagenberg et al., 2004). Therefore, it is remarkable that climate control in pig rooms is generally based on a single temperature measurement outside the AOZ, thereby assuming perfect mixing in the room.

There are three practical reasons for positioning the temperature sensor for climate control outside the AOZ: (1) animals cannot damage the sensor, (2) the temperature measured in the AOZ is probably affected by animals near the sensor, and (3) with currently used conventional controllers, the temperature sensor must be located where fluctuations in the conditions of the inlet air (input to the climate system) can be sensed quickly. This is necessary for fast response of the ventilation and heating system, because it contributes to a constant climate in the AOZ. Locating the sensor in the AOZ (output of the climate control system) could make the response of the climate control system too slow.

The first reason can easily be anticipated; the sensor can be placed in a protective cage. Locating the sensor at a proper position and/or choosing the right dimensions for the cage can probably solve the second problem. The third problem is less easy to solve but very important, especially in ventilation systems where fresh air can flow relatively direct into the AOZ. These ventilation systems are based on a combination of displacement and mixing of air, e.g., door ventilation or ground channel ventilation systems (Breum et al., 1989; Van Wagenberg and Smolders, 2003). In such systems, fresh air enters the room via the operator walkway. Fresh air and room air mix in the mixing zone (MZ), positioned just above and behind the pen partition (as seen from the operator walkway, figs. 1 and 2) that separates the operator walkway from the pens. In this zone, the temperature sensor of a conventional P controller or on/off controller should be positioned to monitor fast fluctuations in the conditions of the incoming air. In practice, it is assumed that the temperature in the MZ is close to the temperature in the AOZ, but the correlation between the temperatures in those two zones is not known. Therefore, it is important to study this relation in detail and

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then determine whether or not it is advantageous to take AOZ temperature into account in ventilation and heating control.

Moving the controller sensor away from the MZ makes conventional P or on/off control algorithms less suitable, especially for the mentioned ventilation systems. Model-based predictive (MBP) control algorithms can than be advantageous, where the future behavior of the output of a system (based on a model of the system) is used to calculate control actions (De Moor, 1996; Vranken et al., 1998; Janssens et al., 2004). Using those algorithms, the controller sensor can measure the system output (i.e., AOZ temperature), and the controller can take action based on the predicted system output. This can, for example, be advantageous in pig rooms with on/off heating systems, where on/off switching of the heating system results in fluctuations in room temperature (Van Utrecht et al., 2002). Applying an MBP control technique to on/off heating control can result in a system that switches on the heating system before the AOZ actually gets too cold, and switches it off before it gets too warm, resulting in a more stable AOZ temperature. This can be applied in both new and existing buildings.

The objectives of this study were: (1) to evaluate the conventional system of climate control in a practical room with ground channel ventilation for weaned piglets by comparing the temperature in the MZ and the AOZ, and (2) to determine the advantages of controlling the heating system (on/off) based on AOZ temperature with an MBP controller in terms of a more stable AOZ temperature.

MATERIALS AND METHODS

One room with ground channel ventilation was used. The room (7.0 m wide, 12.6 m long, and 3.0 m high) was designed for housing of 180 weaned piglets from 7 kg to approximately 23 kg. It was located at the experimental farm of the Animal Sciences Group in Lelystad, The Netherlands. There were two experimental batches of pigs, each kept for 5 weeks in the period October 2003 to December 2003. The pigs used in the experiment were selected in such way that at day 0 all pigs in the room were within a 2 kg range in weight (for example, between 6.8 and 8.8 kg) and the average pig weight per pen was the same for all pens (i.e., maximum difference of 0.1 kg). The average start weight was 7.8 kg per pig in batch 1 and 8.2 kg in batch 2. The animals had a high health status, resulting in better than average growth performance: the

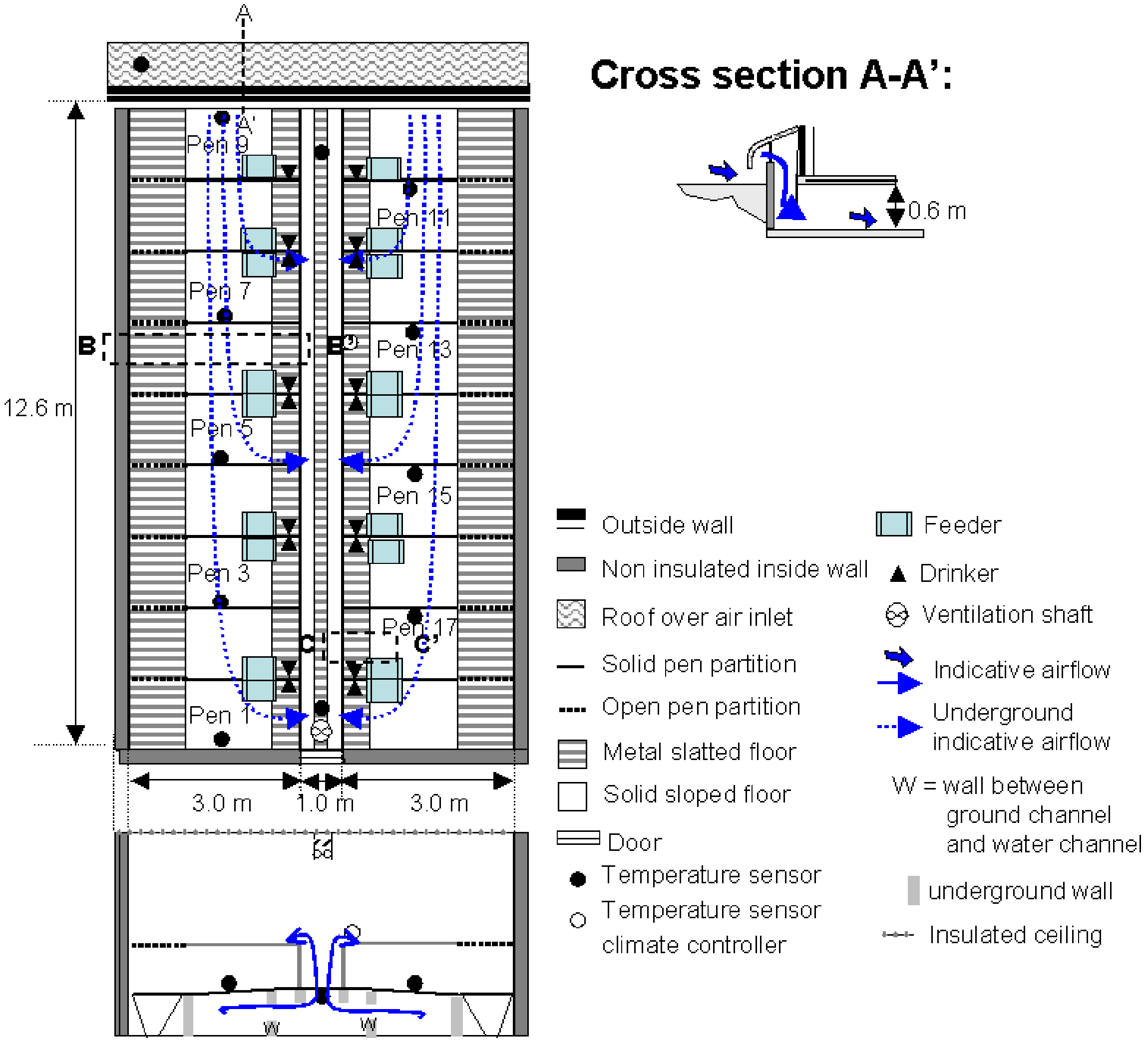


Figure 1. Plan view of the experimental room showing the pens (not all pen numbers are shown), airflow, and locations of the temperature sensors (not to scale). Cross−section A−A' is a detail of the air inlet. Cross−sections B−B' and C−C' are shown in figure 2.

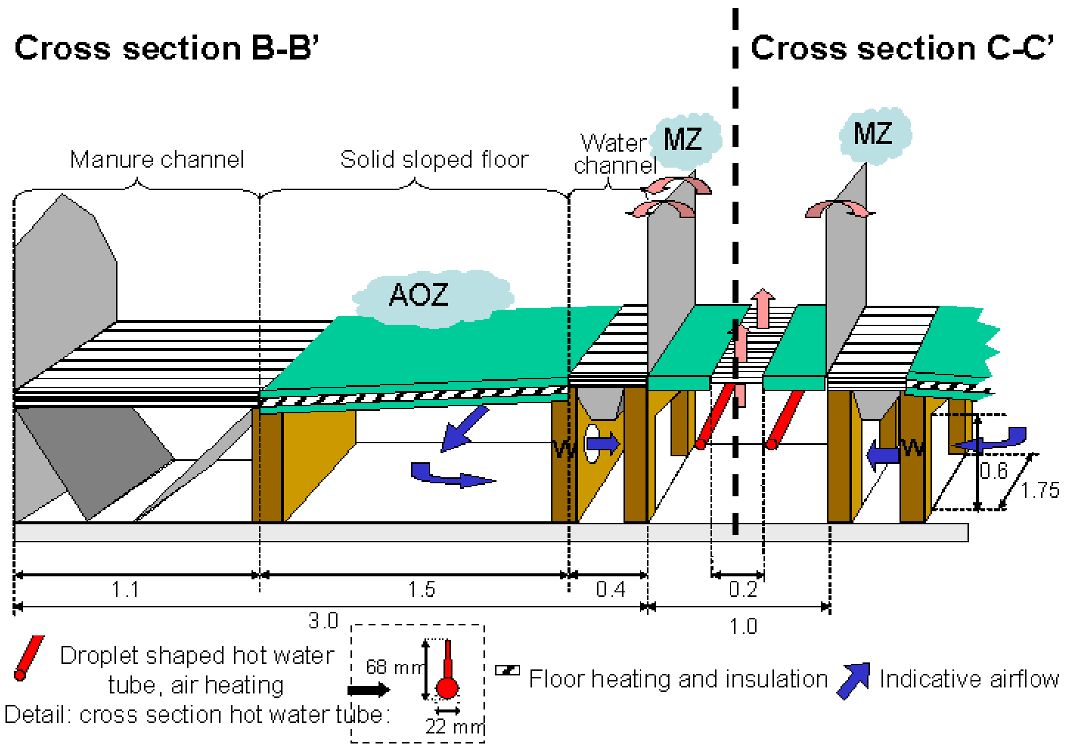


Figure 2. Cross−sections B−B’ and C−C’ of the ground channel (fig. 1) showing the animal−occupied zone (AOZ) and mixing zone (MZ) where sensors were located. The detail cross−section shows a heating tube. All dimensions in m (not to scale).

average growth rate was 522 g per pig per day, and the average feed conversion ratio was 1.51 kg feed per kg growth for the two experimental batches. In comparison, in another experimental farm with a relatively low health status in The Netherlands, the growth rate was 390 g per pig per day and the feed conversion ratio was 1.41 kg feed per kg growth (Van Krimpen et al., 2001).

EXPERIMENTAL ROOM

Figures 1 and 2 show a plan view and cross−sections of the pig room. On each side of the operator walkway (1.0 m wide) were nine pens (3.0 m long and 1.4 m wide) with ten animals per pen. As seen from the operator walkway, in the front of the pens was a metal slatted floor (0.4 m wide) above the water channel, followed by a solid sloped floor (1.5 m wide), and in the back of the pens was a metal slatted floor (1.1 m wide) above the manure channel.

The room had a ground channel ventilation system, as is commonly used in The Netherlands. Fresh air entered the building through openings in the outside wall, which were designed for an airspeed of about 1 m s^{-1} at the maximum ventilation rate. The exterior air inlets were covered with an overhanging roof. Outside air entered the air channels under the insulated solid floors (figs. 1 and 2) and passed through openings in the underfloor walls (indicated with “W” in figs. 1 and 2) between the solid floor and the water channel on both sides of the operator walkway. At the door end of the room, under pens 1, 2, 17, and 18, there was one large opening (1.75 m wide and 0.6 m high, cross−section C−C’ in fig. 2) on either side of the walkway. Eight smaller round openings were distributed along the rest of the wall (cross−section B−B’ in fig. 2), each with a diameter of 0.19 m, spaced 1.24 m on center, and located 0.34 m above ground level. Air flowed through these openings into the air channel under the operator walkway. The air entered the room through a 0.2 m wide slot in the floor of the operator walkway, which was covered with metal slats (50% open) (see fig. 3a).

Next to the operator walkway were solid pen partitions (0.8 m height). Fresh air filled the operator walkway and flowed slowly over the pen partitions into the pens. For all ventilation rates (from 3 to 25 m^3 h^{-1} per piglet), all pens received fresh air directly from the operator walkway. Smoke tests (in which smoke was blown into the incoming air outside the building) were done to visualize the airflow pattern in the building. Figure 3a shows a typical result. The smoke filled the operator walkway starting at the door end of the room. Smoke reached the pens near the door first and the pens near the outside wall last. This non−uniform air distribution over the length of the room was primarily due to the large openings under pens 1, 2, 17, and 18.

Air was removed from the room through a circular ventilation shaft (diameter 0.45 m) in the ceiling above the operator walkway, directly behind the door at 2.5 m height (ceiling height was 3.0 m). To measure the ventilation rate, a two−blade ventilation rate sensor (accuracy <50 m^3 h^{-1}, Fancom BV, Panningen, The Netherlands) was mounted in the ventilation shaft (Berckmans et al., 1991). Additionally, to control the volumetric airflow rate, an automatic valve was mounted in the ventilation shaft.

Climate control was automatic and based on the MZ temperature (also referred to as “room temperature” in this article) measured at a single position. The sensor (time constant to reach 63% of the end value was 200 s) was located above pen 13 (see fig. 1), about 0.15 m above and 0.15 m behind the front pen partition.

Heat was supplied by a hot−water floor heating system, which was controlled independently from the room tempera−

(a) (b)

Figure 3. (a) Smoke test to visualize the airflow pattern from the operator walkway over the pen partitions in the experimental room, and (b) top view of pen 5 (under cold conditions) with indicated AOZ temperature sensor and imaginary "sensor pen" around AOZ sensor (see Discussion section).

ture, and by an air heating system consisting of droplet−shaped hot water tubes under the operator walkway and operated by the climate controller. Both systems are shown in figure 2. When the measured room temperature was lower than the heating setpoint, the climate controller switched on the air heating system by opening a valve, and hot water (between 70°C and 85°C) entered the tubes. The valve closed when the room temperature was equal to or higher than this setpoint, resulting in an on/off control action (with a hysteresis of 0.3°C). The heat transfer rate of the droplet−shaped tubes to the air was approximately 150 W m^{-1}. The maximum heating capacity was 8.4 kW for one room, or 47 W per piglet. The settings for heating and ventilation used in the climate controller are shown in table 1. These settings were based on current practice in the Netherlands.

Extra heat was supplied via the floor heating system during only the first 5 to 10 days. After day 10, the animals lying on the solid floor caused the water temperature in the floor to remain between 27°C and 30°C without extra heat supply.

MEASUREMENTS

Thirteen temperature sensors (accuracy 0.1°C) were installed. One was located outside, and the other 12 sensors were positioned as shown in figures 1 and 2:

- Two sensors (referred to as "air inlet temperature") were mounted in the air channel under the operator walkway 0.1 m under the slats: one near the door (approx. 1 m from the door), and one near the wall (approx. 1 m from the wall).
- One sensor was mounted near the sensor of the climate controller (referred to as "mixing zone temperature" or "room temperature"). The sensor of the climate controller was not logged.
- Nine sensors were mounted in the AOZ of all odd−numbered pens. The sensors were located in the middle of the solid floor, 0.05 m from the side partition on the side opposite the feeder and 0.1 m above the floor. The AOZ sensors were placed in metal protective cages (0.09 m deep, 0.14 m wide, and 0.22 m high) made of iron wire (6 mm diameter) with openings of 25 × 25 mm (fig. 4). In this way, free airflow though the cage was combined with protection against animal interference.

The state of the heating system (i.e., on/off) was derived by analyzing the inlet temperature and outside temperature data. The start of upward steps in inlet temperature, while the outside temperature was stable, indicated when the heating system switched on; moments when the difference between inlet and outside temperatures started to decline indicated that the heating had switched off. Ventilation rate was measured using the ventilation rate sensor. Temperature data and ventilation rate were logged every 2 min, and the state of the heating system was also determined every 2 min.

Table 1. Climate settings for the experimental room.

	Temperature (°C)			Ventilation per Piglet (m^3 h^{-1})[a]	
Day	Air Heating	Floor Heating	Ventilation Setpoint	Min.	Max.
0	26	35	28	3	12
5	24	30	26	4	15
21	21	20	23	6	18
28	20	−−	22	7	22
42	19	−−	21	9	25

[a] Temperature range between min. and max. ventilation = 5°C.

Figure 4. Metal cage to protect AOZ sensors in pens.

DATA ANALYSIS

The AOZ and room temperature data during the two batches were first analyzed graphically to determine the effect of the on/off switching of the heating system on AOZ temperature. To investigate the possible advantages of using the AOZ temperature in a model−based predictive (MBP) controller to control the heating system, several periods (datasets) were selected from the overall dataset (consisting of measurements of approximately 10 weeks). The selection criteria were: (1) the dataset had to cover a period of at least 6 h, (2) the heating system had to switch on and off at least five times to ensure that the dataset contained sufficient information on the dynamic behavior of the system (such dynamics are necessary to identify the model for the MBP controller, presented in the next section), and (3) there should be little or no disturbing effect of animals in the vicinity of the sensor (further explained in the Results section). Five datasets fulfilled these criteria; they were measured during five cold nights (nights 4 and 5 of batch 1, and nights 6, 7, and 8 of batch 2).

Modeling

The five datasets were used to determine a mathematical model between the AOZ temperature (°C) as the output, and ventilation rate ($m^3\ h^{-1}$), outside temperature (°C), and state of the heating system (0/1) as input parameters. These input parameters were chosen because they were expected to explain the majority of the variations in AOZ temperature. In addition, because these data are normally available in modern pig houses, no extra measurements would be required for using the model to predict AOZ temperature. The modeling technique, referred to as dynamic data−based modeling, describes the relation between inputs and output with a relatively simple model (transfer function). This technique has been used in many applications. For example, Aerts et al. (2000) used it to model the response of heat production of broilers to changes in temperature and light intensity. A feature of the data−based model is that it is only valid under the experimental conditions; however, it is simple and therefore suitable for control purposes. In this research, only first−order responses were expected between output and inputs. The following multiple−input, single−output (MISO) model was used:

$$y(k)=\frac{b_{01}}{1+a_1 z^{-1}}\left(u_{1,k-d_1}\right)+\frac{b_{02}}{1+a_1 z^{-1}}\left(u_{2,k-d_2}\right)+\frac{b_{03}}{1+a_1 z^{-1}}\left(u_{3,k-d_3}\right) \qquad (1)$$

where

$y(k)$ = temperature in the AOZ at moment k

b_{0i} and a_1 = model parameters

d_i = time delay between input u_i and output y

z^{-1} = backward shift operator of a difference equation that is defined as $z^{-1}\cdot y(k) = y(k-1)$ (Ljung, 1987)

$u_{1,k-d_1}$ = ventilation rate at moment $k-d_1$

$u_{2,k-d_2}$ = outside temperature at moment $k-d_2$

$u_{3,k-d_3}$ = state of the heating system at moment $k-d_3$.

The model parameters were estimated based on a simplified refined instrumental variable method, as extensively described by Young (1984) and Young and Lees (1993). For parameter estimation, the input and output signals were rescaled by subtracting the average initial setpoint value from each signal. The goodness of fit of the model was expressed in terms of R_t^2, with values greater than 0.7 indicating a good fit.

The parameter estimates in the transfer function can be interpreted to explain the process; the parameters b_{0i} directly indicate the effect of the input on the output. The parameter b_{01} (for ventilation rate) is expected to be negative, i.e., an increase in ventilation rate results in a lower AOZ temperature. The parameters b_{02} and b_{03} (for outside temperature and for state of the heating system, respectively) are expected to be positive.

Based on the model parameters, static (steady−state gain) as well as dynamic (time constant) response characteristics can be calculated. The steady−state gain (SSG_i) is determined by the ratio between the change in the output and the change in the input:

$$SSG_i=\frac{b_{0i}}{1+a_1}=\frac{\Delta y}{\Delta u_i} \qquad (2)$$

where

a_1 and b_{0i} = estimated model parameters

Δy = temperature difference between before and after an imaginary step in input variable u_i

Δu_i = step size.

The time constant describes the time taken to reach 63% ($1-1/e$) of the new steady−state level of the system output (AOZ temperature). It can be determined using:

$$\tau=\frac{-\Delta t}{\ln\left(-a_1\right)} \qquad (3)$$

where

τ = time constant

Δt = sample interval

a_1 = estimated model parameter.

Design of Model−Based Predictive Controller

The model describing the mathematical relation between the state of the heating system and the AOZ temperature in pen 7 for dataset 4 was used in a simulated MBP controller, as if the sensor for climate control was positioned in the AOZ of pen 7. Pen 7 was chosen because it had the highest R_t^2 value of 0.86 (table 2). An existing simulation program in Matlab (2002) was used (Janssens et al., 2004). Fluctuations in outside temperature and ventilation rate for dataset 4 were taken into account as disturbances on the AOZ temperature in pen 7 by multiplying the magnitude of these fluctuations with the calculated SSG_i values.

For testing the simulated MBP controller, two constant setpoints were chosen. One was the average AOZ temperature in pen 7 for dataset 4 (22.72°C), and the other was 1°C higher. In the simulation, the sampling time of the AOZ sensor was set at 1 s.

RESULTS

ROOM TEMPERATURE AND AOZ TEMPERATURE

Figure 5 shows the daily averages of the measured AOZ temperatures in pens 5 and 7 and the daily averages of the

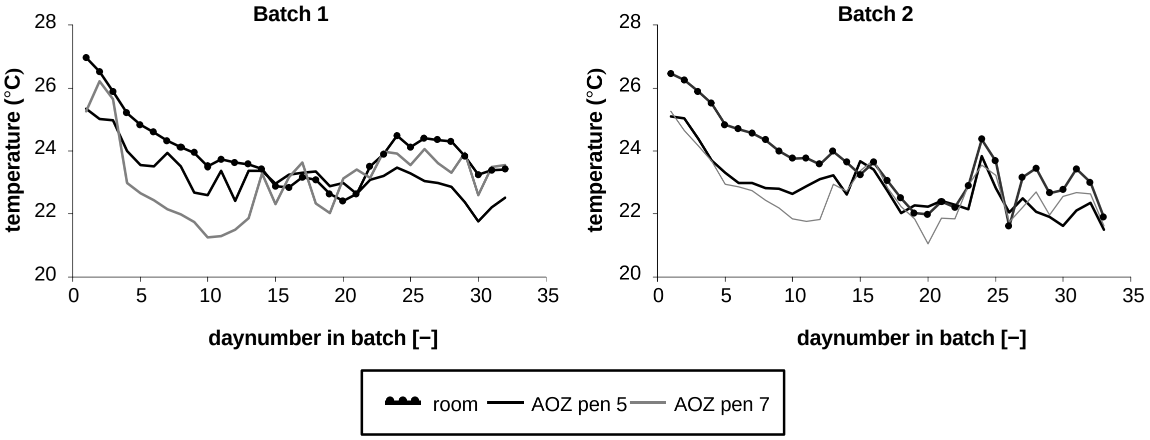


Figure 5. Daily average room temperature and AOZ temperatures measured in pens 5 and 7 during batches 1 and 2.

measured room temperature. For both batches up to day 15, the room temperature was generally higher than the AOZ temperature for all pens, including pens 5 and 7. After day 15, the room temperature and the AOZ temperature were comparable, but after day 21 in batch 1 and day 27 in batch 2, the AOZ temperature again was lower than the room temperature. In this article, further analysis concentrates on the first half of the batch, because the heating systems switched on frequently only in this period.

Figure 6 shows a detailed graph of AOZ temperature in pen 5 and the room temperature during the first four days of batch 2. The AOZ temperature was not only lower than the room temperature but also showed greater fluctuation. Some peaks were likely caused by animal behavior. Our observation was that animal locations have an important effect on the measured AOZ temperature.

In the first half of the batch, the sensors in pens 5 and 7 were largely unaffected by animal behavior because the sensors were located on the side of the pen opposite the feeder. The feeder was an obstacle for fresh airflow coming from the operator walkway. Therefore, behind the feeder, the air velocity was lower, and the young animals preferred to huddle there (see fig. 3b). AOZ temperature measurements behind the feeder were much higher than on the opposite side of the pen, where fewer animals congregated.

The generally lower temperatures in the AOZ indicate that there was more fresh air in the AOZ than around the sensor in the MZ. When the incoming air was relatively cold (compared to room air), a thin layer (several centimeters) of fresh air flowed over the pen partition; the controller sensor in the MZ was located above this layer.

Regarding these results, it seems advantageous to use AOZ temperature for climate control in pig rooms with ground channel ventilation. AOZ temperature is expected to be more representative of the air around the pigs than the room temperature at the current position in the MZ. AOZ temperature is hereby defined as the temperature of the air flowing toward or around a group of pigs. The temperature of still air within a group of pigs is less relevant; at excessively low room temperatures, it is likely the temperature within a group of huddling pigs is within the thermoneutral range, but the animals lying at the edge will be too cold. Therefore, if AOZ temperature is used in climate control, then the sensor must be positioned outside the lying area of the animals and in such a way that animals close to the sensor cannot disturb the measurement. The AOZ sensors in the pens were largely unaffected by the pigs during the first half of both batches.

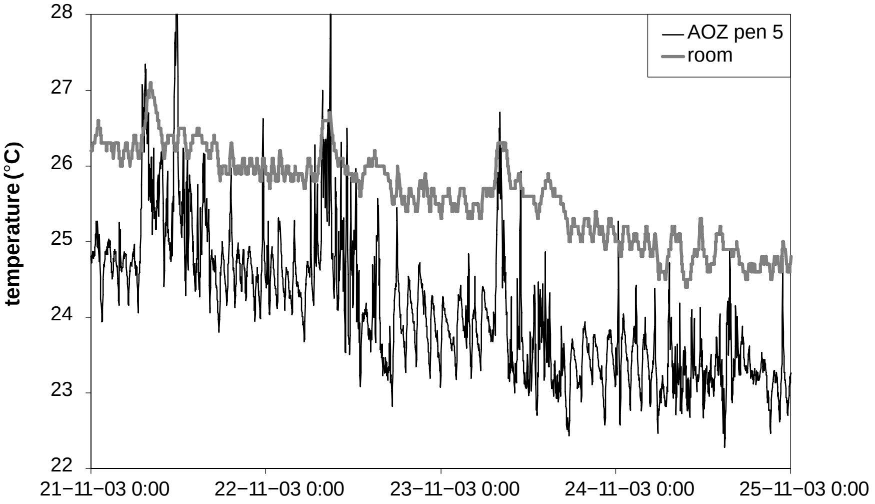
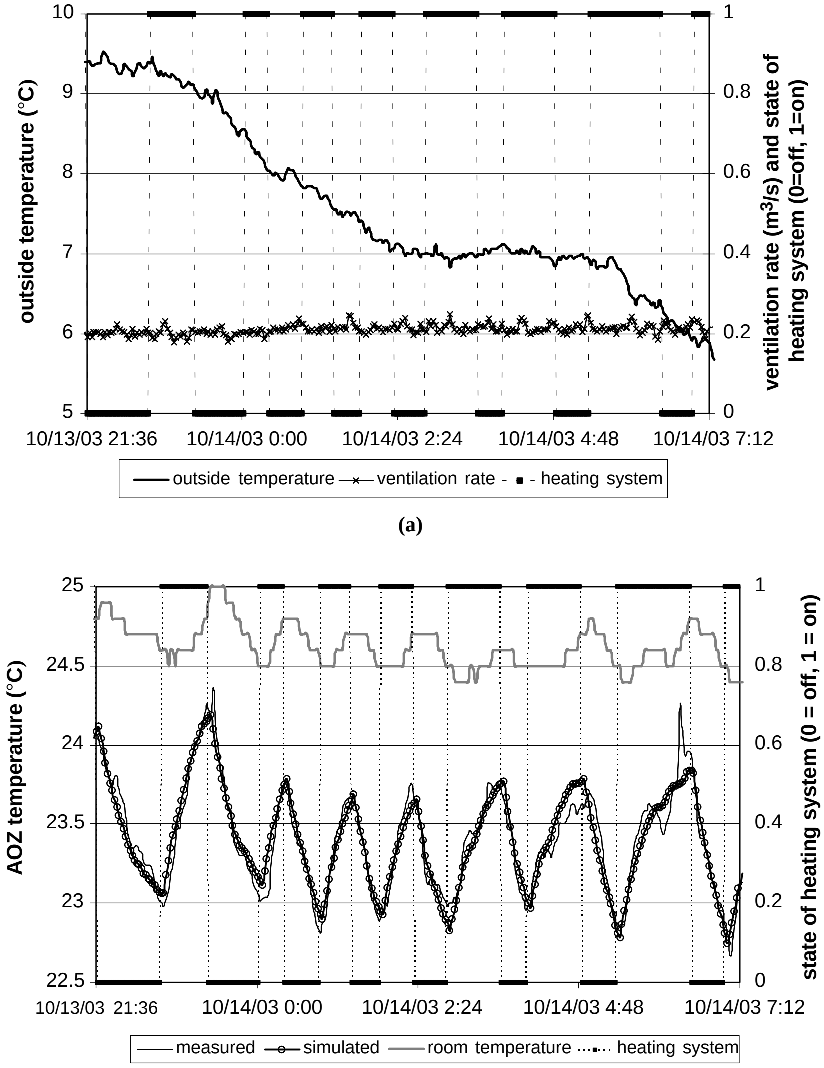


Figure 6. AOZ temperature in pen 5 and room temperature during the first 4 days of batch 2 (measured every 2 min).



(a)

(b)

Figure 7. (a) Course of input variables and (b) room temperature and measured and simulated AOZ temperatures in pen 9 during night of day 5 to 6 in batch 1 (dataset 4).

MODEL-BASED PREDICTIVE CONTROLLER

Figure 7 shows an example of the course of the model inputs (i.e., outside temperature, ventilation rate, and state of the heating system) and output (both measured and simulated AOZ temperature) of the model (pen 9, dataset 4). The simulated AOZ temperature will be addressed later in this article.

Outside temperature decreased with time during the 11 h period. Ventilation rate was relatively constant and at a minimal level, which was representative of all datasets. The heating system was switched on and off eight times. There was a clear response of the state of the heating system on AOZ temperature in pen 9. The room temperature also showed this response, but the fluctuations were much smaller than in the AOZ temperature of pen 9.

This response in AOZ temperature was not clearly observed in the pens close to the door. This was caused by the non−uniform distribution of air inlet openings under the water channel, resulting in more and/or colder fresh air in the front of the room. When the heating system was switched on, there was hardly any increase of the AOZ temperature in the front pens. This problem can probably be solved by better distribution of the openings over the length of the room, and not by implementing a new controller. For this research, the consequence is that the data from the pens in the front of the room (i.e., pens 1, 3, and 17) were deemed not suitable for designing and testing the new control algorithm for the heating system. Therefore, only data from the other pens were subsequently considered.

Modeling

A total of 30 datasets was available for modeling (5 night datasets × 6 pens); for all cases, the model in equation 1 was used. An example of a model output is shown in figure 7b, in which the calculated AOZ temperature is almost identical to the measured AOZ temperature. Variation in the input variables apparently can explain the observed variation in AOZ temperature. Tables 2 and 3 show the pen−average results and the dataset−average results, respectively, for all fitted models. The R_t^2 (average 0.77) shows that the temperature could be modeled accurately.

Table 2. Pen−average goodness of fit (R_t^2) of the model, average time delays (ATD = d_i) and model parameters with standard errors (SE) for each input variable, and the calculated steady−state gains (SSG_i) and time constant τ.

		Model Parameters											Average Steady−State Gains[a]			
		a_1		Ventilation Rate, b_{01}			Outside Temp., b_{02}			State of Heating, b_{03}						
Pen	Avg R_t^2	Avg	SE	ATD (min)	Avg b_{01}	Avg SE b_{01}	ATD (min)	Avg b_{02}	Avg SE b_{02}	ATD (min)	Avg b_{03}	Avg SE b_{03}	SSG_1	SSG_2	SSG_3	Avg τ (s)
5	0.67	−0.884	0.283	0.8	−0.000346	0.000181	11.6	0.0141	0.0056	7.2	0.110	0.032	−0.00235	0.123	1.109	1132
7	0.86	−0.861	0.142	0.8	−0.000549	0.000135	11.6	0.0118	0.0029	4.4	0.162	0.023	−0.00433	0.087	1.445	1023
9	0.80	−0.858	0.167	1.2	−0.000778	0.000201	11.6	0.0155	0.0041	5.2	0.168	0.028	−0.00556	0.107	1.271	879
11	0.80	−0.862	0.174	1.6	−0.000304	0.000143	12	0.0222	0.0048	4	0.174	0.030	−0.00207	0.176	1.397	872
13	0.84	−0.918	0.150	0.4	−0.000459	0.000101	11.2	0.0129	0.0026	4.8	0.101	0.014	−0.00511	0.168	1.267	1448
15	0.68	−0.917	0.236	0	−0.000427	0.000208	12	0.0142	0.0052	6.8	0.133	0.034	−0.00519	0.211	1.745	1541
Avg	0.77	−0.883	0.192	0.8	−0.000477	0.000161	11.7	0.0151	0.0042	5.4	0.141	0.027	−0.00410	0.145	1.372	1150

[a] SSG_1 is for ventilation rate (°C (m^3 h^{-1})$^{-1}$), SSG_2 is for outside temperature (°C °C^{-1}), and SSG_3 is for the state of the heating system (°C [−]$^{-1}$).

The fitted models were validated using the same datasets as used for estimation of the model parameters. The models were not validated using other datasets (cross−validation). Because the models will be used for control of time−varying systems, the model parameters will be updated regularly based on on−line measurements. Consequently, cross−validation, i.e., evaluating the model with a new dataset to which the parameters were not adjusted (Ljung, 1987), is not relevant, since the model parameters change as a function of time.

Tables 2 and 3 show variation in time delay between inputs. Time delay for outside temperature was highest (11.7 min average); this is expected, because the air first has to pass the air channel and the operator walkway before reaching the pens. As expected, ventilation rate had the least time delay (0.8 min average); an increase in ventilation rate almost directly affects the heat removal from the AOZ. Ventilation rate and outside temperature were relatively stable; they did not cause much of the fluctuations in the AOZ temperature, as indicated by the low SSG values. Steady−state gain of the state of the heating system (SSG_3) was highest in all cases (1.37°C average), indicating that the AOZ temperature increased 1.37°C after the heating system was switched on. The time delay before the AOZ temperature started to increase was 5.4 min on average, and from then the time to reach an AOZ temperature increase of 0.86°C (τ, 63% of 1.37°C) was 19.2 min on average.

Design of Model−Based Predictive Controller

Inputs, disturbances, controller output (new course of the state of the heating system), and a simulated course of the temperature in pen 7 are plotted in figure 8 for the setpoint of 22.72°C.

The temperature disturbance in figure 8c shows the calculated course of the AOZ temperature as if there were no heating system and assuming that a constant setpoint needs to be added on the vertical axis. During the first 4 h, there were some fluctuations and some periods when the temperature became colder than the setpoint. After 4 h, the calculated AOZ temperature became lower than the setpoint because of the decrease in outside temperature (fig. 8a). However, the heating system switched on and off during this 11 h period, which is shown figure 8b. In figure 8a, the AOZ temperature with the MBP controller shows quicker and smaller fluctuations and stays closer to the setpoint than the AOZ temperature in the conventional situation. These fluctuations are inevitable when working with a heating system that can only switch on and off and that has a constant and relatively high heat supply. Possible methods to reduce these fluctuations are mentioned in the Discussion section.

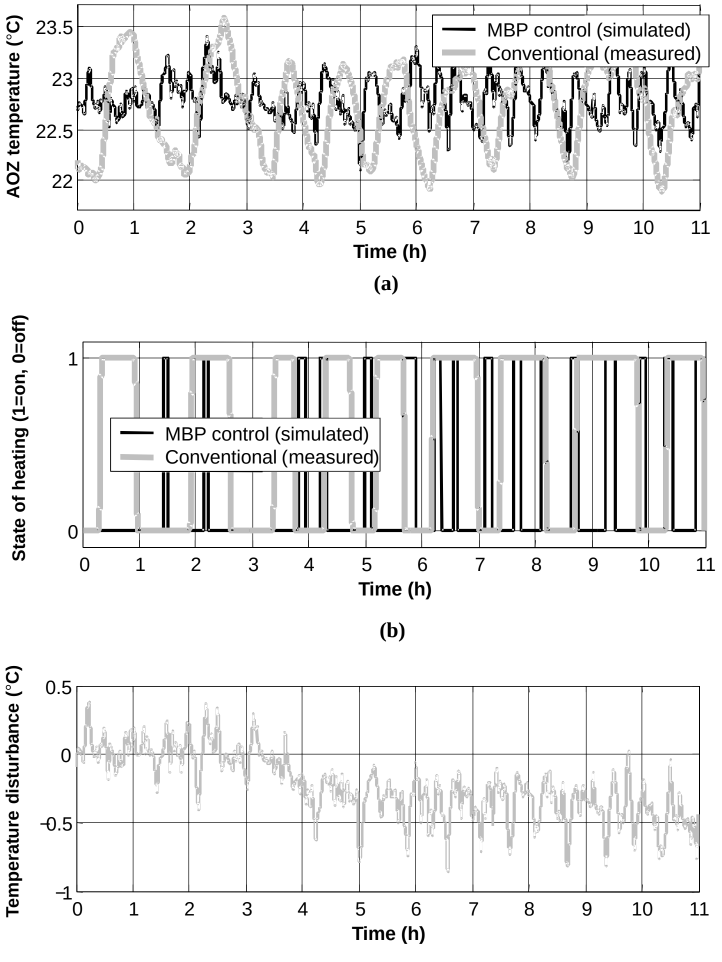
Figure 8b shows that the conventional control system (as measured) switched on and off nine times during the 11 h period. With MBP control, the heating system switched on and off 16 times. The average times the heating system was on were 38 min for conventional control and 7.5 min for MBP control; the total time that the heating system was on during the 11 h period was 346 min with conventional control and 119 min with MBP control. When the setpoint in pen 7 was 23.72°C (not shown in fig. 8), the heating system switched on and off 26 times during the 11 h period, with an average time of 17 min and a total time of 452 min.

To investigate if a more stable climate was also reached in the other pens, the AOZ temperature in the other pens was predicted using the models from the previous section. Outside temperature, ventilation rate, and the simulated

Table 3. Dataset−average goodness of fit (R_t^2) of the model, average time delays (ATD = d_i) and model parameters with standard errors (SE) for each input variable, and the calculated steady−state gains (SSG_i) and time constant τ.

		Model Parameters											Average Steady−State Gains[a]			
		a_1		Ventilation Rate, b_{01}			Outside Temp., b_{02}			State of Heating, b_{03}						
Data Set	Avg R_t^2	Avg	SE	ATD (min)	Avg b_{01}	Avg SE b_{01}	ATD (min)	Avg b_{02}	Avg SE b_{02}	ATD (min)	Avg b_{03}	Avg SE b_{03}	SSG_1	SSG_2	SSG_3	Avg τ (s)
1	0.82	−0.918	0.162	1.6	−0.000297	0.000098	12	0.0207	0.0053	5.7	0.131	0.021	−0.00383	0.272	1.710	1559
2	0.84	−0.881	0.178	1.3	−0.000430	0.000112	12	0.0116	0.0034	7	0.160	0.028	−0.00367	0.097	1.384	990
3	0.68	−0.827	0.251	0.6	−0.000960	0.000351	11	0.0230	0.0067	6	0.143	0.037	−0.0059	0.149	0.976	761
4	0.80	−0.914	0.169	0.3	−0.000285	0.000109	12	0.0107	0.0034	3.7	0.151	0.026	−0.00317	0.128	1.751	1358
5	0.72	−0.877	0.200	0	−0.000414	0.000138	11.3	0.0096	0.0022	4.7	0.122	0.023	−0.00388	0.081	1.041	1080
Avg	0.77	−0.883	0.192	0.8	−0.000477	0.000161	11.7	0.0151	0.0042	5.4	0.141	0.027	−0.00410	0.145	1.372	1150

[a] SSG_1 is for ventilation rate (°C (m^3 h^{-1})$^{-1}$), SSG_2 is for outside temperature (°C °C^{-1}), and SSG_3 is for the state of the heating system (°C [−]$^{-1}$).



(a)

(b)

(c)

Figure 8. Inputs and output of the controller (pen 7, setpoint 22.72°C): (a) AOZ temperature, (b) state of the heating system, and (c) temperature disturbance. Black lines represent the simulated MBP control system, and grey lines are based on measurements with the conventional control system.

course of the state of the heating system were used as inputs. Figure 9 shows the course of the temperature in pen 13 with both conventional and MBP control. For both setpoints, the temperature in pen 13 with MBP control was more stable than the measured temperature, indicating that a more stable temperature can be achieved in pens other than where the sensor is mounted.

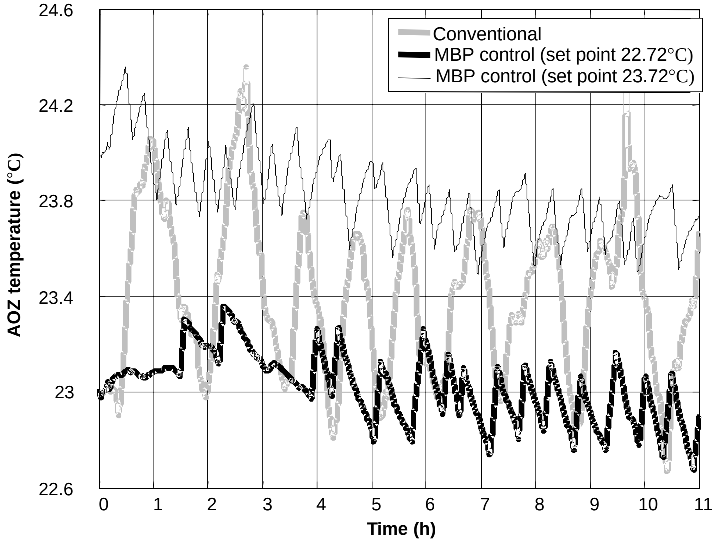


Figure 9. Course of the AOZ temperature in pen 13 (dataset 4) with conventional control (gray line) and MBP control (black lines) using the controller sensor in pen 7 with two different setpoints.

Table 4. Average AOZ temperatures (˚C) (dataset 4) and standard deviations (SD) for the temperature course in the conventional situation and in the simulation with two different MBP controller setpoints (sensor in pen 7) during the 11 h period.

	Conventional (setpoint in MZ was 24°C)		MBP control (setpoint in AOZ was 22.72°C)		MBP control (setpoint in AOZ was 23.72°C)	
Pen	Avg	SD	Avg	SD	Avg	SD
5	23.50	0.45	23.71	0.15	24.53	0.16
7	22.72	0.43	**22.79**	0.21	**23.68**	0.21
9	21.98	0.44	21.45	0.15	22.21	0.18
11	22.79	0.56	21.89	0.20	23.13	0.22
13	23.40	0.33	23.02	0.14	23.83	0.17
15	23.92	0.44	23.27	0.14	24.08	0.17
Avg	23.05	0.44	22.69	0.17	23.57	0.18

In table 4, the average AOZ temperatures and standard deviations are shown for both conventional and MBP control. The table contains data from all pens where temperature was measured in the experiment (except for pens 1, 3, and 17) and results of the simulated MBP controller with two setpoints. The standard deviation is a good indicator of AOZ temperature stability in this situation, because the controller had a constant setpoint and because there were some differences in temperature between pens.

Table 4 shows that, in all pens, the standard deviation of the measured temperatures is always higher than that of the simulated temperatures with MBP control. The average simulated temperature in pen 7 is close to the setpoints (bold numbers in table 4) in both simulations. MBP control clearly results in a more stable AOZ temperature in all pens, which is expected because the heating system was switched on and off more frequently. The average standard deviation of the AOZ temperature during 11 h of a cold night is reduced by more than 50%.

Table 4 also shows that there are temperature differences between the pens. Pens 5 and 15 were the warmest, while pen 9 was the coldest. Those differences cannot be reduced by MBP control; the design of the air inlet system and/or the insulation of the walls need improvements to reduce these temperature differences.

DISCUSSION

When AOZ temperature is used for controlling the climate, the disturbing effect of the animals on the measurements must be minimized. These disturbances could be reduced by placing the sensor in a small “sensor pen” of, for example, 0.2 m wide, especially for measuring the temperature above the solid floor (see fig. 3b). The “sensor pen” will improve the measurement; however, it will reduce the available pen area.

In the datasets that we used for modeling, we assumed that animal proximity had no effect on the measurements. This assumption cannot be proved using the level of analysis described in this article, but it is supported by the fact that the course of the temperature in the AOZ could be modeled with a data−based dynamic modeling technique (R_t^2 = 0.77) by taking the outside temperature, the ventilation rate, and the state of the heating system as inputs. Apparently, most of the variations in AOZ temperature could be related to changes in these inputs. Using these models to control AOZ temperature in an MBP controller under cold conditions clearly has advantages in terms of keeping the AOZ temperature more constant. The heating system is switched on and off more frequently, resulting in more frequent but much smaller fluctuations in the AOZ temperature.

This study did not investigate whether or not the same result could be achieved by using a conventional control algorithm with the temperature sensor in the AOZ. It is expected that MBP control gives a better result than conventional control because a conventional controller first needs to detect a difference with the setpoint before taking action, while MBP control uses the future behavior of the system. Therefore, MBP control is in general better suited to using a sensor signal from the output of a system. Especially in systems with a time delay, like the climate system presented here, where it took 5.4 min on average for the heat supply to increase the AOZ temperature, MBP control has proven advantages (De Moor, 1996).

An advantage of implementing the MBP control algorithm in practice is that all the required input variables for predicting AOZ temperature are already being measured in a modern pig house. While it requires an adaptation in the controller, MBP control does not require extra measuring equipment, making it a relatively inexpensive system. A more expensive solution to the problem of an unstable AOZ temperature, due to the heating system switching on and off, could be to make the heat supply variable (Van Utrecht et al., 2002). In many cases, this would still require an adapted climate controller (in practice, the heating system output of most climate controllers is not proportional) and an adapted heating system with a mixing valve.

Finally, using AOZ temperature in climate control, as described in this article, has not been tested in practice. The research was based on practical measurements with the current sensor position. Based on the analysis of the data, it seems that under cold conditions, there are advantages to moving the sensor to the AOZ. It is not known how the system will function under warmer conditions when the inside temperature is controlled by changing the ventilation rate. Therefore, the next step is to test the controller in combination with an AOZ temperature sensor and determine whether the expected technical advantages are within reach.

CONCLUSION

In a pig room with ground channel ventilation, the animal−occupied zone (AOZ) and room temperature showed differences; AOZ temperature was lower during the first period of a batch, and it showed more fluctuations than room temperature. The low−frequency on/off switching of the heating system resulted in larger fluctuations in AOZ temperature than in room temperature.

Using AOZ temperature for controlling the climate could be more advantageous than the conventional system where climate control is based on room temperature. The position of the sensor in the AOZ has to be carefully considered, because animals close to the sensor influence the measurement. Furthermore, the use of a model−based predictive (MBP) controller instead of a conventional controller is useful, because an MBP controller takes action based on the calculated future behavior of the system.

The measured course of the temperature in the AOZ could be accurately modeled with a data−based dynamic modeling technique ($R_t^2 = 0.77$). The model was integrated in a simulated model−based predictive controller to control the state of the heating system to prevent the large fluctuations in AOZ temperature. The simulated AOZ temperature was more stable during cold periods, the standard deviation of the AOZ temperature during an 11 h cold period was reduced from 0.44°C to 0.18°C.

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