Measurement, evaluation and control of the microclimate in rooms for weaned piglets

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Measurement, evaluation and control of the microclimate in rooms for weaned piglets

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Abstract

The Animal Occupied Zone (AOZ), or the microclimate, in a room for weaned piglets is roughly the zone between 0 and 50 cm above the floor of the pen. It is distinguished from the macroclimate, which is the average climate of a pig room. The ability to create and maintain an optimal climate in the AOZ is an important aspect of ventilation system performance, and was studied in this thesis in rooms for weaned piglets.

The effectiveness of removal of air contaminants and heat from the AOZ highly depended on the type of ventilation system. It was highest in a room with ground channel ventilation. In a room with door-ventilation, it varied largely over the pens. In the room with porous ceiling ventilation the heat production of the animals resulted in an upward airflow above the lying area, which lowered AOZ contaminant removal effectiveness.

For a good insight in thermal environment in the AOZ, air velocities were measured in the AOZ by an ultrasonic anemometer. The location of the anemometer in a pen appeared to be important and in a door-ventilated room there were differences in average air velocity between the pens.

To indicate the quality of the thermal environment piglets in a batch are exposed to, two evaluation methods were introduced. The first uses solely AOZ air temperature; the other the kata-value (KV), which combines air velocity and air temperature. The methods result in numerical indicators, based on the duration and the magnitude of excess of AOZ thermal conditions outside the Thermo Neutral Zone. These methods proved to be useful tools in the technical evaluation of climate-systems, and the value of the indicator for “too warm” conditions significantly affected animal performance. Comparison of both indicators learnt that air temperature is the most critical variable to be measured to characterize the AOZ climatic conditions, but for recognition of “too cold” conditions KV clearly has additive value.

Simulated AOZ climatic conditions were compared with measurements in a door-ventilated room, and showed that the simulation technique is a powerful tool for the design of a ventilation system, but needs to be calibrated with data from real farming situations.

In a conventional climate control system in a room with ground channel ventilation AOZ temperature was lower and showed greater fluctuations than room temperature. Model predictive control including AOZ temperature measurement strongly reduced the temperature fluctuations in the AOZ.

Voorwoord

Wat is nu een goed onderzoek? Met deze vraag heb ik vaak geworsteld afgelopen jaren. Naast klanttevredenheid en kloppende begrotingen tellen ook goede wetenschappelijke publicaties. Daarbij moest mijn onderzoek aansluiten bij vragen die in de praktijk leven rondom klimaatbeheersing in varkensstallen, waardoor dit zou bijdragen aan verbetering van het klimaat waarin onze varkens gehuisvest worden. Tijdens dit promotieonderzoek was bovengeschetst krachtenveld een uitdagende en soms ook afleidende achtergrond. Maar na 5 jaar is de klus dan toch geklaard, en ken ik in ieder geval de belangrijke randvoorwaarden voor een goed onderzoek.
Ten eerste is samenwerking zeer belangrijk, onderzoek in een praktijkstal is teamwork. Ik heb altijd kunnen rekenen op hulp van collega onderzoekers, collega's van de meetploeg en van de praktijkcentra: Mark, Henk (2*), Theo, Mart en vele anderen. Ook zorgt samenwerking voor inspiratie en wordt ermee voorkomen dat het wiel op te veel plekken opnieuw uitgevonden wordt. Internationaal heb ik samengewerkt met mijn Deense collega Bjarne, en met mijn collega's in Leuven, waarbij ik met name Jean-Marie en Daniel wil noemen. Alle samenwerkingspartners, bedankt.
Ten tweede is goede begeleiding uitermate belangrijk. De regelmatige bijeenkomsten met de begeleidingscommissie hielden me scherp en op gang. Als commissie waren we ook aardig op elkaar ingespeeld. Gerard, mijn eerste promotor, met enorm veel fysisch technische inbreng. Als buitenstaander van de varkenshouderij leverde jij een continue check op een heldere en eenduidige rapportage. Jos, tweede promotor en zootechneut met een talent om zaken zo helder en wetenschappelijk te analyseren. Leo, als co-promotor was jouw inbreng een enorme hoeveelheid varkenshouderijervaring, maar ook om het proces te bewaken. Als laatste in dit rijtje Nico, die eigenlijk altijd al varkenshouder wilde worden. Jouw rol in mijn promotieonderzoek was vooral de inbreng van praktische aspecten, maar omdat je ook mijn clustermanager bent hadden we ook naast dit onderzoek zeer veel met elkaar te maken. Begeleiders, enorm bedankt.
Ten derde is het voor een goed onderzoek essentieel dat een onderzoeker mensen om zich heen heeft die hem motiveren en stimuleren. Vrienden en familie, het schrijven van dit proefschrift kende een paar dalletjes waar ik met jullie doorheen gewandeld ben. Nu heb ik hier weer meer tijd voor. Enne, Marloes en Stan, wat hebben we het toch goed met ons drietjes.

Contents

CHAPTER 1

General Introduction

Indoor climate in pig husbandry

Most of the 122 million pigs in the European Union (EU-15, 2004) are kept indoors, to protect them from negative environmental impacts and to control their environment in order to optimise production. Generally, this results in much better animal performance compared to outdoor production (Enfält et al., 1997; Sather et al., 1997). Furthermore, keeping pigs indoors enables the manure to be collected and reduces pollutant emissions (Williams et al., 2000; Van Wagenberg et al., 2004). The climate in livestock buildings has to be controlled (Zhang et al., 2001a), and the key process for that is ventilation. The problem is that an adequate control of air distribution in the 3-dimensional space occupied by animals, is still lacking. Therefore, this thesis focuses on the relationship between the 3-dimensional ventilation and the optimal climatic environment for weaned piglets.

The standard pig house is subdivided into rooms containing a number of pens. Each room houses a batch of pigs of the same age and therefore with the same thermal needs. Piglets are born in a farrowing room, and when 4 weeks old (bodyweight circa 8 kg) are moved to a room for weaned piglets. At 10 weeks of age (25 kg) they are moved to the grower-finisher room. Commonly, indoor climate is controlled per room primarily by controlling the ventilation rate and additionally by heating.

It is extremely important to keep weaned piglets in the right climatic environment. Directly after weaning these animals are subjected to many stresses, including being separated from the sow, being moved, and changing from milk to a solid diet (Le Dividich and Herpin, 1994; McCracken et al., 1995, Le Dividich and Sève, 2000). In addition, after the first few days it is important that the climate is right, as production results and health are negatively affected by adverse climatic conditions (Herpin and Lefaucheur, 1992; Le Dividich and Herpin, 1994; Hamilton et al., 1998; Madec et al., 1998).

Ventilation systems for weaned piglets

The most common ventilation systems in rooms for weaned piglets are mechanical systems in which fans extract the air from the room. Fresh air enters the room via an air inlet system, and the type of air inlet system generally determines the air distribution in the room.

In the Netherlands three types of air inlet systems are common in rooms for weaned piglets. The first is porous ceiling ventilation, primarily based on mixing of fresh air with room air. It is generally applied in rooms with fully slatted floors. Fresh air enters the room through small ducts in the ceiling or through a porous part of the ceiling (Aarnink and Wagemans, 1997; Lee et al., 2004). The other two systems are primarily based on displacement of air and are generally used in rooms with partly slatted floors. Door-ventilation uses the operator walkway in the room as an air inlet channel; fresh air enters the room through an opening in the door (Van ‘t Klooster, 1994). Ground channel ventilation supplies fresh air via an under floor air duct and through openings in the floor of the operator walkway (Aarnink and Wagemans, 1997; Van Wagenberg et al., 1999). In recent years, interest in this system has increased. All systems have a problem relating to the 3-dimensional ventilation and air supply to the animals (Vranken, 1999; Zhang et al., 2001b; Lee et al., 2002).

Climatic demands of pigs

The climatic environment can be subdivided into two aspects. The first is the thermal climate of the pig, which is determined by air temperature, air velocity and heat transfer due to conduction (example: floor heating) or radiation (example: heating lamps). The second aspect is air composition (air quality), i.e. the concentration of contaminants and oxygen in the air. Typical aerial contaminants in pig rooms are ammonia, carbon dioxide, dust and vapour.

A widely accepted range for the optimal thermal climate for the pig is defined as the Thermo Neutral Zone (TNZ), which is the range of thermal conditions in which the metabolic rate of the pig is minimal (Klooster et al., 1989; CIGR, 1999; Quiniou et al., 2000; Van Ouwerkerk, 2000; CIGR, 2002). The limits of the TNZ depend on animal characteristics such as body weight and feed intake. They are mostly expressed in air temperature, but factors like air

velocity and radiative heat loss are important as well (Le Dividich and Herpin, 1994; Van Ouwerkerk, 2000). Another problem is that the effect of periodical short-term exposure of the piglet to conditions outside the TNZ is unknown.
Furthermore, in an optimal climatic environment, the concentrations of contaminants such as ammonia, carbon dioxide and dust should be as low as possible (Robertson et al., 1990) or at least below defined limits (Van ‘t Klooster et al., 1989; Scientific Veterinary Committee, 1997; Donham and Cumro, 1999).

There are four practical reasons why creating an optimal climate is so important for the pigs.

- Production efficiency: It is known that climatic conditions influence feedintake, growth and feed conversion ratio of pigs. In cold conditions, more energy is needed to maintain the body temperature, which has a negative effect on the feed conversion ratio (Herpin and Lefaucheur, 1992; Le Dividich and Herpin, 1994; Hessing and Tielen, 1994). Under hot conditions outside the TNZ, the pigs will eat less and therefore grow slower (Forbes, 1995; Nienaber et al., 1996; Collin et al., 2001; Collin et al., 2002). Also, high concentrations of dust and ammonia are known to reduce performance (Drummond, 1980; Wathes et al., 2004).
- Animal health: Climatic conditions are known to influence the health of the animals. Periods of cold conditions outside the TNZ or high concentrations of bacteria (attached to dust particles) in the air can cause respiratory and other diseases, resulting in more use of medicine and a higher mortality (Verhagen, 1987; Robertson et al., 1990; Köfer et al., 1993; Le Dividich and Herpin, 1994, Hamilton et al., 1998; Madec et al., 1998). When pigs are ill, production efficiency and animal welfare are obviously reduced.
- Animal welfare: Climatic conditions in terms of thermal comfort and availability of fresh air affect animal welfare directly (Scientific Veterinary Committee, 1997). In choice tests pigs prefer fresh air above air containing ammonia (Wathes et al., 2002). Adverse climatic conditions can cause tail biting (Van de Berg, 1982).
- Pen fouling and emissions: Under warm conditions, pigs in pens with a partly slatted floor tend to lie on the cooler slats. As a result, they will dung and pass urine on the solid floor, which causes pen fouling (Aarnink et al., 2001), unhygienic conditions, higher concentrations of the contaminant ammonia in the air and higher emissions of ammonia (Ni, 1998).

Microclimate

It is known that the air in a ventilated room is never homogeneously mixed. There are zones of different climatic conditions, especially in a densely populated pig-room with a high internal heat production. Near the inlet of fresh air the temperature and the concentration of contaminants will be relatively low. Near the sources of heat and contaminants (animals, manure) both temperature and contaminant concentrations will be higher. The airflow pattern in the room determines the temperature and contaminant distribution in the room and is linked to the occurrence of climatic zones (Randall and Armsby, 1983; Hoff et al., 1992; Puma et al., 1999).

The climatic zones of concern in a pig room are the zone where the pig farmer does his work (working conditions) and the zone where the animals live: the Animal Occupied Zone (AOZ). The AOZ is roughly the zone between 0 and 50 cm above the floor of the pen (Hoff, 1995; Hoff et al., 1995; Heber et al., 2001). In this thesis the focus is on the climate in the AOZ, i.e. the microclimate. It is distinguished from the macroclimate in the room, which is the average climate of the room (figure 1).

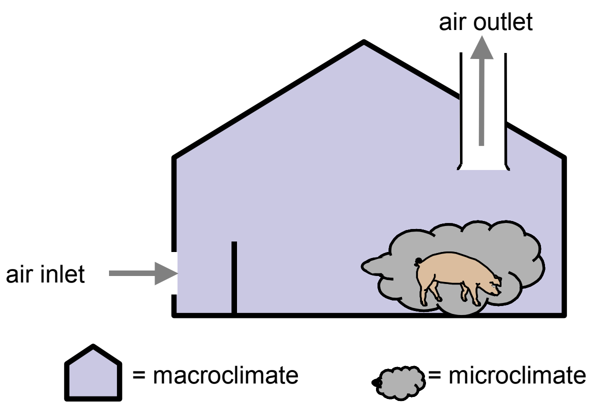

Figure 1. The macroclimate in a pig room and the microclimate in the Animal Occupied Zone (AOZ)

The ability to create and maintain an optimal climate in the AOZ is probably the most important aspect of ventilation system performance (Zhang et al., 2001a), especially in rooms for weaned piglets. Although this factor is so important, very little is known about patterns of the climatic conditions the piglets are exposed to when housed in rooms with different ventilation systems. The research described in this thesis sets out to rectify this.

Objective

The objective of this research was to improve microclimate for weaned piglets by answering the question how to measure, evaluate and control the microclimate in rooms for weaned piglets. Specifically, the study sets out:

- to find measuring systems and strategies for AOZ climatic conditions that could be used in real-scale rooms;
- to measure the effect of the air inlet system on AOZ climatic variables;
- to develop and apply new criteria for evaluating the thermal environment in the AOZ;
- to test a computer simulation technique for predicting AOZ climate conditions;
- and to develop an improved control system based on AOZ temperature.

Outline of this thesis

Chapter 2 examines how AOZ climatic variables depend on the ventilation system. In real-scale rooms occupied by weaned piglets, with ground channel ventilation, porous ceiling ventilation and door-ventilation, temperature and CO_2 concentration in the AOZ were measured, to derive how the ventilation system contributes to AOZ climate control. We determined the effectiveness of the ventilation in terms of removing heat and aerial contaminants from the AOZ.

Supplying a large amount of fresh air in the AOZ is a desirable feature of a ventilation system, however, the thermal climate should stay within TNZ limits. For a good insight in thermal environment in the AOZ, the air velocity has to be considered. Chapter 3 describes how air velocities were measured in the AOZ by an ultrasonic anemometer to investigate air velocity differences in various pens of one room in order to analyse the importance of air velocity measurements.

Chapter 4 focuses on parameters for indicating the quality of the thermal environment piglets in a batch are exposed to. Batch average AOZ conditions do not take into account the fluctuations of temperature and air velocity over time. Therefore two new evaluation parameters were introduced. The first was based solely on the AOZ air temperature, the other was based on the kata-value (*KV*), which combines air velocity and air temperature and indicates the heat loss from the animal to the environment. Chapter 4 describes the methodology and an experiment in which the two parameters were applied and compared in a door-ventilated room. The spatial distribution of the parameters and the response of the animals to the value of these parameters were studied.

Computer simulations (computational fluid dynamics) can predict 3 dimensional distributions of climatic factors in ventilated rooms. In chapter 5 the simulation results of AOZ climatic conditions are compared with measurements in a door-ventilated room. The level of agreement between measurements and simulation shows if and how the numerical simulation technique has to be refined to be an efficient tool in the design of ventilation systems for pig rooms.

In chapter 6 the need of incorporating AOZ temperature instead of macroclimate temperature in a climate control system is explored. The focus was on the on/off heating system control in a room with ground channel ventilation. Both macroclimate and AOZ temperature were measured and compared, to investigate the temperature differences. The AOZ temperature measurements were used to develop data-based models that can predict the effect of the state of the heating system on AOZ temperature. These models were used in a simulated control system. The advantages of this system, with controller sensor position in the AOZ, were determined and expressed in terms of a more stable AOZ temperature.

The general discussion and conclusions are presented in chapter 7.

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CHAPTER 2

Contaminant and Heat Removal Effectiveness of Three Ventilation Systems in Nursery Rooms for Pigs

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Abstract

In this research, three ventilation systems (ground channel, porous ceiling, and door-ventilation) were tested on their performance in supplying fresh air to the animal occupied zone (AOZ), each in a room for 70 weaned piglets. Measurements of the CO_2 concentration and temperature of the inlet air, at one point in the AOZ and in the outlet air were recorded every 36 minutes for three successive batches. Less frequent measurements were done on the CO_2 concentration in two other points in the AOZ. System effectiveness was expressed as the contaminant removal effectiveness (CRE) for CO_2 and the heat removal effectiveness (HRE): CRE or HRE equals 1 when the CO_2 concentration or temperature in the AOZ equals that of the outlet air. Values lower than 1 reflect higher CO_2 concentrations or temperatures within the AOZ; values higher than 1 the reverse.

In all rooms, the value of CRE or HRE varied in time by varying the ventilation rate. CRE was highest in the room with ground channel ventilation, varying with measurement location. CRE was 1.39 on average and HRE was 1.13 on average in the middle of the pen. CRE was higher closer to the air inlet and lower further to the back of the pen, closer to the outlet, because air renewal was based on displacement of old air by fresh air. In the room with door-ventilation, CRE was 1.20 and HRE was 0.95 at a point in the second half of the room in the back of a pen. Air passed over the operator walkway to the back of the room, and back over the pens, resulting in a decreased CRE in the pens closer to the door that acted as an air inlet. In the room with a porous ceiling, CRE values were lower. At one sampling point, CRE was 1.01 and HRE was 0.94. In the lying area of the animals in the back of the room, CRE values were lower than at a sampling point in the front of the room. In the lying area, the heat production of the animals resulted in an upward airflow, which lowered the CRE.

Keywords. Pig housing, Ventilation systems, Air quality, Air distribution, Ventilation effectiveness.

Introduction

Air quality and quality of the microclimate in a pig facility can be characterized by the concentration of contaminants (e.g., ammonia, dust, and bacteria) and by the air temperature, humidity, and air velocity in the animal occupied zone (AOZ), since high concentrations of contaminants and/or high temperatures negatively affect animal health and animal production (Stombaugh et al., 1969; Andreasen et al., 1999; Prunier et al., 1997; Nienaber et al., 1996). Too low air temperatures or high air velocities (draft) in the AOZ also significantly affect animal health, animal behavior, and animal production, especially for weaned piglets (Scheepens et al., 1991a, 1991b). Climatic factors are also technical indicators related to animal welfare (Bockisch et al., 1999), and pigs prefer fresh air above ammoniated air (Smith et al., 1996).

The air within a pig facility contains contaminants, moisture, and heat released by animals, feed, floor surface, and slurry. Contaminated air, moisture, and heat are removed through ventilation. The ventilation system distributes fresh air in the building. The effectiveness with which contaminants and heat are removed by various ventilation systems needs to be well understood. Improving ventilation effectiveness is an important strategy for reducing contaminant concentrations in animal houses (Zhang et al., 2001).

Several ventilation system designs are commonly used in pig rooms. However, little is known of the relationship between the air displacement in the AOZ and the ventilation system design, which determines the airflow pattern in the room. Mathematical models (CFD) predict airflow patterns in empty test rooms without obstacles (Harral and Boon, 1997; Bjerg et al., 1999). The complex environment of an occupied pig room, where animal presence and animal activity significantly affect airflow pattern characteristics (Smith et al., 1999) and the distribution of contaminants, has not been simulated.

Research relying on practical measurements has shown that displacement ventilation without mixing provides more fresh air to the zone of occupancy than dilution ventilation, which ideally requires perfect mixing (Breum et al., 1989), and that a sidewall inlet combined with a high outlet, and thus an upward flow, more effectively removes certain contaminants from the central operator walkway than a downward flow (Breum et al., 1990).

Practical measurements have also shown that the location of the sources of contaminants in the pig room has important effects on contaminant concentration levels and distribution. For example, contaminant concentration (including ammonia and CO_2) measured by Lavoie et al.

(1997) at 1.5 m above the floor of the operator walkway in the center of a pig room showed that significantly lower concentrations could be achieved by locating the air outlet near the source of the contaminants.
Measurements have also been used (Aarnink and Wagemans, 1997) to determine that the air quality (measured in terms of ammonia and dust) in pig facilities is better with a low air inlet, in the floor of the operator walkway, and a low air outlet than with a high diffuse inlet combined with a high outlet.
The research presented below uses practical measurements to gain insight into airflow patterns and effectiveness of ventilation in the AOZ for three ventilation systems commonly used in nursery rooms for pigs. Air quality measurements (CO_2 and temperature, excluding air velocity) in the AOZ of each system were taken for three batches of weaned piglets under practical conditions.

Materials and Methods

Theory

The effectiveness of contaminant removal from the AOZ is expressed by the contaminant removal effectiveness (CRE) (Liddament, 1993). The CRE value is determined by local measurements of concentrations of (gaseous) contaminants emitted in the pig room. CRE value at an arbitrary point *p* at moment *t* for any contaminant is defined as:

$$\mathrm{CRE}_{x,p,t} = \frac{\left(\mathrm{C}_{x,e,t} - \mathrm{C}_{x,i,t}\right)}{\left(\mathrm{C}_{x,p,t} - \mathrm{C}_{x,i,t}\right)} \qquad \textbf{(1)}$$

where

$\mathrm{CRE}_{x,p,t}$ = dimensionless CRE at point *p* at moment *t* for contaminant *x*
$\mathrm{C}_{x,e,t}$ = concentration of contaminant *x* in the outlet air at moment *t* (mg/m^3)
$\mathrm{C}_{x,p,t}$ = concentration of contaminant *x* at point *p* (AOZ) at moment *t* (mg/m^3)
$\mathrm{C}_{x,i,t}$ = concentration of contaminant *x* in the inlet air at moment *t* (mg/m^3).

The effectiveness of the removal of heat from the AOZ can be expressed analogously by the heat removal effectiveness (HRE). Equation 1 can also be used to calculate HRE by replacing the local concentrations with the local temperature values.
CRE and HRE would be equal to 1 in a perfectly mixed air space. In a room with perfect plug flow from inlet to outlet and homogeneously distributed sources of contaminants and heat, CRE and HRE values decrease from an infinite number in the inlet to 1 in the outlet. However, in practice, no ventilation system is perfect plug flow or perfect mixing. All ventilated air spaces show gradients in temperature, humidity, contaminants, and dust (Price et al., 1999) due to airflow patterns and different contaminant source locations, resulting in values of CRE and HRE above or below 1. CRE values above 1 indicate that fresh air enters the AOZ first and then passes the contaminant sources on its way to the outlet, which should indicate effective air displacement in the AOZ. CRE values below 1 indicate that the contaminant concentration in the AOZ exceeds the contaminant concentration in the outlet air. These lower values can occur when part of the fresh air is removed from the room without causing air displacement in the AOZ, or when the arbitrary point *p* is close to the source of the contaminant. Low values of CRE indicate high contaminant levels that are not being efficiently removed from the AOZ.
This research focuses on CRE and HRE in the AOZ. Effective removal of contaminants from the AOZ (CRE > 1) is desirable at low ventilation rates to contribute to good air quality in the AOZ and energy savings for heating because less ventilation air is needed. Effective removal of heat from the AOZ (HRE > 1) is desirable at high ventilation rates when ventilation is mainly for temperature control of the AOZ.

Experimental Rooms

In three occupied nursery rooms for pigs, CO_2 and temperature measurements were done to determine CRE and HRE values. The experiment was carried out at the Experimental Pig Farm at Sterksel, The Netherlands.
The rooms were located next to each other in one building. Internal height was at 2.40 m in the three rooms. A plan and a cross-section of the three rooms are shown in figure 1, together with the locations of the sampling points. The rooms were built as representative copies of the three ventilation systems most applied in practice.

Room 1 - Ground Channel Ventilation

Two groups of 35 weaned piglets were housed in room 1. Floor area was 0.30 m^2/pig, of which 0.17 m^2 was slatted and 0.13 m^2 was solid. Pens were 3.30 m × 3.65 m. Heating was provided by hot water pipes against the wall in the operator walkway and in the solid floor in the pens.

Ventilation air was preheated up to 5°C in the central passage, where it flowed into the ground channel through an opening in the floor. Air flowed under the solid floor of the pens and toward the operator walkway, passing the space under the manure trays, which were located under the plastic slats. Air entered the room through a slot (0.06 m in width) over the length (7.30 m) of the floor of the operator walkway. Average air velocity in the slot varied between 0.13 and 1.11 m/s as ventilation varied between 3 and 25 m^3/h per animal. In the design it was expected that fresh air would flow with a low velocity through the inlet slot and fill the operator walkway. From there it was expected to flow via the front of the pen over the pen partition (0.60 m height) towards the animals. In the pen, the air was expected to flow to the back of the pen, supplying fresh air in the AOZ and removing contaminants from the AOZ. The ventilation process was based on displacement and mixing of air. The ventilation was driven by a fan (diameter 0.35 m) located in the back of the room at a height of 1.00 m, 0.05 m from the back wall, and 0.70 m from the sidewall.

Room 2 - Porous Ceiling Ventilation

Two groups of 35 weaned piglets were housed in room 2. Floor area was 0.30 m^2/pig. Pens were 7.30 m × 1.80 m. Heating was provided by four hot water radiation tubes, 0.30 m under the ceiling and equally distributed over the width of the room.

Ventilation air came directly from outside through an opening in the outside wall above the porous ceiling. It was then expected to flow through the porous ceiling, which consisted of porous board covered with one layer of glass wool. The entire ceiling functioned as air inlet, and inlet velocity was very low. Fresh air was expected to mix with the air present in the room and result in a homogeneously mixed airspace. The ventilation was driven by a fan (diameter 0.40 m) located in the back of the room at 1.80 m height, 0.05 m from the back wall, and 3.45 m from both sidewalls.

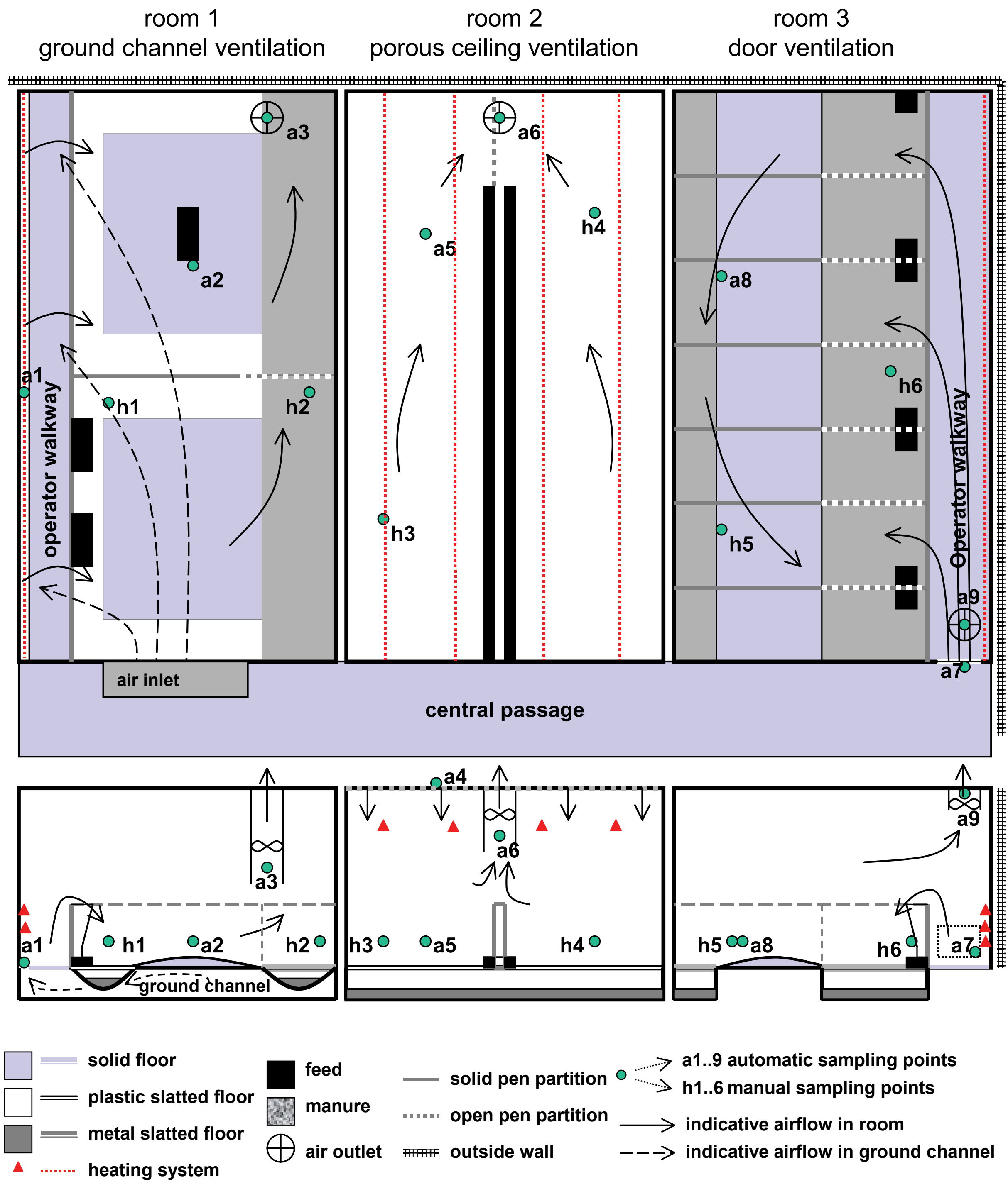

Figure 1. Plan and cross-section of the building with the three experimental rooms.

Room 3 - Door-ventilation

Seven groups of 10 weaned piglets were housed in room 3. Floor area was 0.30 m^2/pig, of which 0.16 m^2 was slatted and 0.14 m^2 was solid. Pens were 1.04 m × 3.30 m. Pens were numbered; the pen closest to the door was pen number 1 and farthest from the door was number 7. Heating was provided by hot water pipes against the external wall in the operator walkway and in the solid floor in the pens.

Ventilation air first passed the central passage, where it was preheated up to 5°C, and then entered the room through an opening (0.37 m × 0.67 m) in the door (underside of opening at 0.20 m height) into the operator walkway. Air velocity in the opening varied between 0.24 and 1.96 m/s as ventilation varied between 3 and 25 m^3/h per animal. Fresh air filled the operator walkway (width 0.90 m and length 7.30 m) and was expected to flow via the front of the pen over the pen partition (height 0.60 m) toward the animals. It was then expected to flow to the back of the pen, supplying fresh air in the AOZ and removing contaminants from the AOZ. The ventilation process was based on displacement and mixing of air. The ventilation was driven by a fan (diameter 0.35 m) located in the front of the room directly behind the door at 2.25 m height, 0.35 m from the front wall, and 0.25 m from the sidewall.

Table 1. Climate settings in experimental rooms (set point heating = 2°C under set point ventilation; temperature range between minimum and maximum ventilation = 5°C).

Ventilation System	Day	Floor Heating (°C)[a]	Set point Ventilation (°C)	Ventilation per Animal (m^3/h)	
				Min.	Max.
Ground Channel Ventilation	0	On	28	3	12
	5	On	25	4	15
	20	Off[b]	24	6	18
	42	Off	22	9	25[c]
Porous Ceiling Ventilation	0	N.A.[d]	28	4	13
	5	N.A.	26	5	16
	20	N.A.	24	7	25
	42	N.A.	22	11	35
Door-ventilation	0	On	28	3	12
	5	On	25	4	15
	20	Off	24	6	18
	42	Off	22	9	25

[a] Water temperature in floor = 45°C.
[b] Floor heating off at day 17.
[c] In batch 3, the maximum ventilation was set at 33 m^3/h per animal.
[d] N.A. = not available.

Climate Control

Control of ventilation rate and heating in all three rooms was based on the measured inside temperature and settings in the climate controller. Climate settings were copied from those advised in practice for the various ventilation systems and are listed in table 1. At day number 0, the piglets were put into the room.

Measurements and Recordings

Five sampling points were located in each room, three of which were in the AOZ. Four considerations determined the locations of these sampling points in the AOZ:

- The presence of the sampling point may not affect animal behavior in the pen.
- If differences in CO_2 concentration or temperature are expected within the AOZ, then the sampling points have to be distributed in a way that this can be measured.
- At least one of the sampling points has to be located in the expected lying area of the animals.
- The locations of the sampling points have to be practical for the animal keeper.

Three sampling points per room were connected to an automatic measuring system to measure CO_2 concentration and temperature using respectively a gas monitor (Bruel and Kjaer infrared monitor type 1302, accuracy ±5.0 mg/m^3) and thermocouples (accuracy ±0.75% of the measured value). Data were recorded successively every 36 minutes. These sampling points were located in the air inlet, in the air outlet, and in the AOZ approximately 0.2 m above the floor and are indicated with the letter "a" in figure 1.

Two more sampling points in the AOZ were connected to a manual measuring system (Anagas CD 98) to measure CO_2 concentration, which was recorded once each day during the first week of the batch and three times per week later (alternating between morning and afternoon). These sampling points were located approximately 0.2 m above the floor and are indicated with the letter "h" in figure 1.

From automatic and manual sampling points, air samples were taken and transported through a Teflon tubing system to the CO_2 sensor outside the rooms in such way that animal behavior and airflow characteristics were not influenced. The thermocouples and Teflon tubing system were protected against the animals by perforated iron pipes. In the ventilation exhaust shaft, the ventilation rate was measured continuously with a measuring fan (accuracy <50 m^3/h) and recorded every 10 minutes. Lying behavior of the animals was recorded once per week in terms of the average number of piglets lying within a 1 m diameter circle around each sampling point. These recordings were done directly after the manually recorded CO_2 concentrations.

The status of the heating (on/off) was recorded (when hot water entered the heaters) during the second half of the second batch and during the third batch. There was one recording for floor heating and room heating; in the data it was not specified which kind of heating was used in the room.

Table 2. Minimum, maximum, and mean values of the recorded CO_2 concentrations, outside air temperatures, and inlet air temperatures per batch.

	Ground Channel Ventilation			Porous Ceiling Ventilation			Door Ventilation		
Batch	I	II	III	I	II	III	I	II	III
Start Date	17 Jan	14 Mar	1 May	24 Jan	14 Mar	1 May	24 Jan	14 Mar	1 May
End Date	21 Feb	13 Apr	13 Jun	21 Feb	13 Apr	13 Jun	21 Feb	25 Apr	13 Jun
No of Observations	885	741	1074	732	760	1081	723	1067	998
CO_2 inlet air (mg/m^3)									
Min.	692	675	630	666	663	624	683	646	621
Max.	1240	1240	1270	955	1040	1120	1220	1220	1200
Mean	803	789	744	737	742	733	771	757	733
Outside air temp. (°C)									
Min.	-11.2	-3.9	3.4	-11.2	-3.9	3.4	-11.2	-3.9	3.4
Max.	11.0	19.8	32.7	11	19.8	32.7	11	25.8	32.7
Mean	3.5	6.8	16.4	3.6	6.8	16.4	3.6	7.9	16.4
Inlet air temp. (°C)									
Min.	8.0	9.0	12.0	-0.07	2.7	6.9	6.0	6.5	10.7
Max.	15.0	17.4	24.4	13.5	19.7	31.5	15.3	22.4	29.4
Mean	11.1	13.0	17.0	7.3	10.2	17.2	10.0	13.2	18.0

Experimental Conditions

All piglets were born at the same farm. After weaning, piglets were selected to obtain comparable groups of animals in the rooms. The data presented in this article were collected during three batches between January 2000 and June 2000. Each day, the lights were on in the rooms between 7:30 a.m. and 4.30 p.m.

Table 2 lists the mean values of the outside and inlet conditions during the experiment. In the room with porous ceiling ventilation, the inlet air generally had lower temperatures and CO_2 concentrations because the inlet air for this room was extracted directly from outside and not from the central passage.

Table 3 lists animal production results during the experimental batches. Despite some differences, production results in all three rooms were good, indicating that all three ventilation systems functioned well. Production results were not analyzed because the experimental setup was not suitable for determining differences in production caused by the ventilation system. Beside the difference in ventilation systems, there were differences in group size, floor layout, and feeding systems. To compare animal production results, all these factors should be comparable, and the treatment (ventilation system) should be changed between the rooms.

Table 3. Average animal production over the three batches.

	Ground Channel Ventilation	Porous Ceiling Ventilation	Door Ventilation
Mean start weight per piglet (kg)	8.27	8.10	7.60
Mean end weight per piglet (kg)	25.30	23.76	22.96
Mean growth per day per piglet (kg)	0.435	0.421	0.394
Mean feed conversion ration (kg/kg)	1.62	1.71	1.68

Data Analyses

The CO_2 concentrations and temperatures collected by the automatic system were checked for missing data. In cases when one value (inlet, AOZ, or outlet) was missing, so that the CRE and HRE could not be calculated, the other two measurements were removed. The three automatic measurements per room (inlet, AOZ, and outlet) were defined as one observation and used to calculate CRE and HRE with equation 1 (number of observations in table 2). The CO_2 concentrations in the AOZ collected by the manual system were combined with the nearest (in time) CO_2 concentrations in inlet and outlet as measured by the automatic system. This was defined as one observation and was used to calculate CRE and HRE with equation 1.

The average value and standard deviation (SD) of CRE and HRE were determined per sampling point. In a graphical analysis, the values of CRE and HRE were plotted against ventilation rate. No statistical analysis could be carried out because of interrelations between animal weight, heating status, inside temperature, and ventilation rate.

Results

CO_2 Concentration, Air Temperature, CRE, and HRE

The average values and SD of the measured CO_2 concentrations and air temperatures in the AOZ with automatic measuring systems are listed in table 4. The average values briefly summarize the performance of the ventilation system at the sampling points. The SD values indicate the variation in the data and were expected to be high because the measured variables directly relate to the ventilation rate, which varies during a batch and between batches depending on day number and outside climate.

The lowest average ventilation rate was measured in the room with ground channel ventilation, where the average CO_2 concentration in the AOZ was lowest. The highest average ventilation rate was measured in the room with porous ceiling ventilation, where the average CO_2 concentration and air temperature in the AOZ were highest. In batch 3 in all rooms, the inside temperature and the average ventilation rate were higher than in the other batches because of higher outside temperatures, resulting in lower CO_2 concentrations.

The average values for CRE and HRE are listed in table 5. In the room with ground channel ventilation, CRE and HRE values were highest, as expected. In the room with porous ceiling ventilation, CRE was lowest. In all rooms, there were differences between the CRE value and the HRE value, indicating that distribution of heat is not similar to distribution of CO_2. In all rooms, SD values for CRE were higher than for HRE, as there was more variation in CO_2 concentration than in temperature.

CRE at Different Sampling Points

For the three rooms, table 6 lists average CRE values based on all manually recorded CO_2 concentrations and the comparable automatically recorded CO_2 concentrations (average over the three batches).

Table 4. Average of the automatically recorded CO_2 concentration (mg/m^3) in the AOZ, temperature (°C) in the AOZ, and ventilation rate (m^3/h per piglet) during the three batches (SD in parentheses).

Batch	Ground Channel Ventilation			Porous Ceiling Ventilation			Door-ventilation		
	CO_2 Conc.	Temp.	Vent.	CO_2 Conc.	Temp.	Vent.	CO_2 Conc.	Temp.	Vent.
1	2534 (613)	22.3 (1.66)	5.7 (1.55)	3126 (718)	23.0 (1.14)	6.3 (1.49)	3186 (454)	22.0 (1.35)	5.4 (1.32)
2	2405 (537)	23.1 (1.74)	5.7 (1.51)	3276 (837)	24.3 (1.06)	7.1 (1.95)	2664 (528)	22.9 (1.28)	8.8 (4.18)
3	2307 (800)	24.2 (1.75)	11.2 (5.60)	2657 (817)	25.5 (1.64)	12.6 (6.36)	2466 (703)	24.7 (1.77)	11.8 (5.33)
Average	2408 (682)	23.3 (1.91)	7.9 (4.61)	2974 (841)	24.4 (1.68)	9.2 (5.21)	2729 (646)	23.3 (1.86)	8.9 (4.84)

Table 5. Average CRE and HRE during the three batches (SD in parentheses).

Batch	Ground Channel Ventilation		Porous Ceiling Ventilation		Door-ventilation	
	CRE	HRE	CRE	HRE	CRE	HRE
1	1.41 (0.37)	1.08 (0.10)	1.04 (0.24)	0.97 (0.06)	1.12 (0.18)	0.92 (0.07)
2	1.46 (0.37)	1.16 (0.10)	0.99 (0.24)	0.93 (0.08)	1.22 (0.24)	0.96 (0.08)
3	1.29 (0.35)	1.16 (0.14)	0.99 (0.29)	0.93 (0.24)	1.26 (0.29)	0.96 (0.11)
Average	1.39 (0.37)	1.13 (0.12)	1.01 (0.26)	0.94 (0.16)	1.20 (0.25)	0.95 (0.10)

Table 6. Average CRE at different sampling points (SP) over three batches (SD in parentheses) and average number of animals within 1 m diameter circle around sampling point.

Ground Channel Ventilation (69 observations)			Porous Ceiling Ventilation (73 observations)			Door-ventilation (72 observations)		
SP	CRE	No. of Animals	SP	CRE	No. of Animals	SP	CRE	No. of Animals
a2	1.36 (0.38)	3.4	a5	0.96 (0.24)	3.8	a8	1.21 (0.21)	3.4
h1	1.83 (0.97)	4.6	h3	1.33 (0.47)	2.0	h5	0.77 (0.18)	2.1
h2	1.02 (0.35)	1.3	h4	0.76 (0.24)	4.5	h6	1.12 (0.33)	1.7

In the room with ground channel ventilation, the differences in CRE value among the different sampling points were the largest, as expected, because the ventilation is based on displacement of air. This type of ventilation caused variation across the room. The CRE value was highest at h1 because this sampling point was situated relatively close to the fresh air supply in the operator walkway. The CRE value was lower at sampling point a2 and lowest at sampling point h2 because these points were situated in the middle and in the back of the pen, closer to the air outlet. The CRE value decreased as air flowed from the front to the back of the pen. The influence of the number of animals close to a sampling point was not clear (table 6).
In the room with porous ceiling ventilation, the differences in CRE value among the different sampling points were larger than expected (table 6), indicating that the air was not homogeneously mixed. The reason for this was the heat production of the animals. At the lying areas of the animals, there was an upward airflow, which resulted in a downward flow of fresh air at places where no animals were lying. The number of animals around sampling point h4 was high compared to the number of animals around sampling point h3 (table 6), which explains the higher CRE value at h3. This implies that CRE values in the AOZ with porous ceiling ventilation are lower at places where animals are lying.
In the room with door-ventilation, the CRE value was highest at sampling point a8 in the back of one pen. At sampling point h5, the CRE value was considerably lower than at sampling points h6 and a8. This was not expected, but it can be explained by the airflow pattern. As fresh air entered the room, much air flowed to the end of the room until it reached the end wall, especially at high air velocities in the inlet. This resulted in more air displacement in the pens farther from the door. Old air from these pens flowed back toward the door over the other pens, which resulted in a lower CRE value in pens closer to the door. The CRE value at location h6 is lower than at location a8, indicating that CO_2 concentration is higher in the front of pen number 4 than in the back of pen number 5. This could mean that even more air enters pen 4 via pen 5 than directly from the operator walkway. The layout of the room, with seven pens instead of two pens, had an effect on the distribution of animals, as sources of CO_2 and heat, in the room.

Analysis of the Value of CRE and HRE

The graphical analysis of the effect of ventilation rate on the value of CRE and HRE for the three rooms is presented in the three graphs in figure 2. The left axes show the average values and the trend line of CRE and HRE per ventilation class (0.43 m^3/h per animal). As mentioned before, the CRE value is of main concern during periods with low ventilation and the HRE during periods with high ventilation. The right axes in figure 2 show the percentage of the time that the ventilation rate was within a certain ventilation class.

In the room with ground channel ventilation, the HRE value was constant and the CRE value decreased with increasing ventilation. Reason for this decreasing CRE value is that air velocity in the inlet slot caused the air jet to reach higher into the room with increasing ventilation, which changed the airflow pattern. At higher ventilation rates, the CRE and HRE values show more variance because there were fewer observations with high ventilation rates. For porous ceiling ventilation, CRE was again relatively constant with increasing ventilation, and HRE decreased with increasing ventilation. This can be explained by increased short-circuiting of the airflow: some fresh air entering through the ceiling is removed from the room before reaching the AOZ and without removing heat from the AOZ.

In the room with door-ventilation, with increasing ventilation, the HRE stays on almost the same level, close to 1, as CRE increases. The reason for this is the air velocity in the door. With increasing ventilation, the air velocity in the door increases, which changes the airflow pattern, resulting in more air movement toward the back of the room closer to the sampling point.

No effect of the recorded status of room heating on the values of CRE and HRE was found. The measurement system could not determine this effect. Although the moment that hot water entered the room was recorded, this only indicated the start time of the heating; heat transfer continues after hot water stops flowing through the tubes. In addition, in the rooms with ground channel ventilation and door-ventilation, no distinction was made between hot water heating of the room air and floor heating.

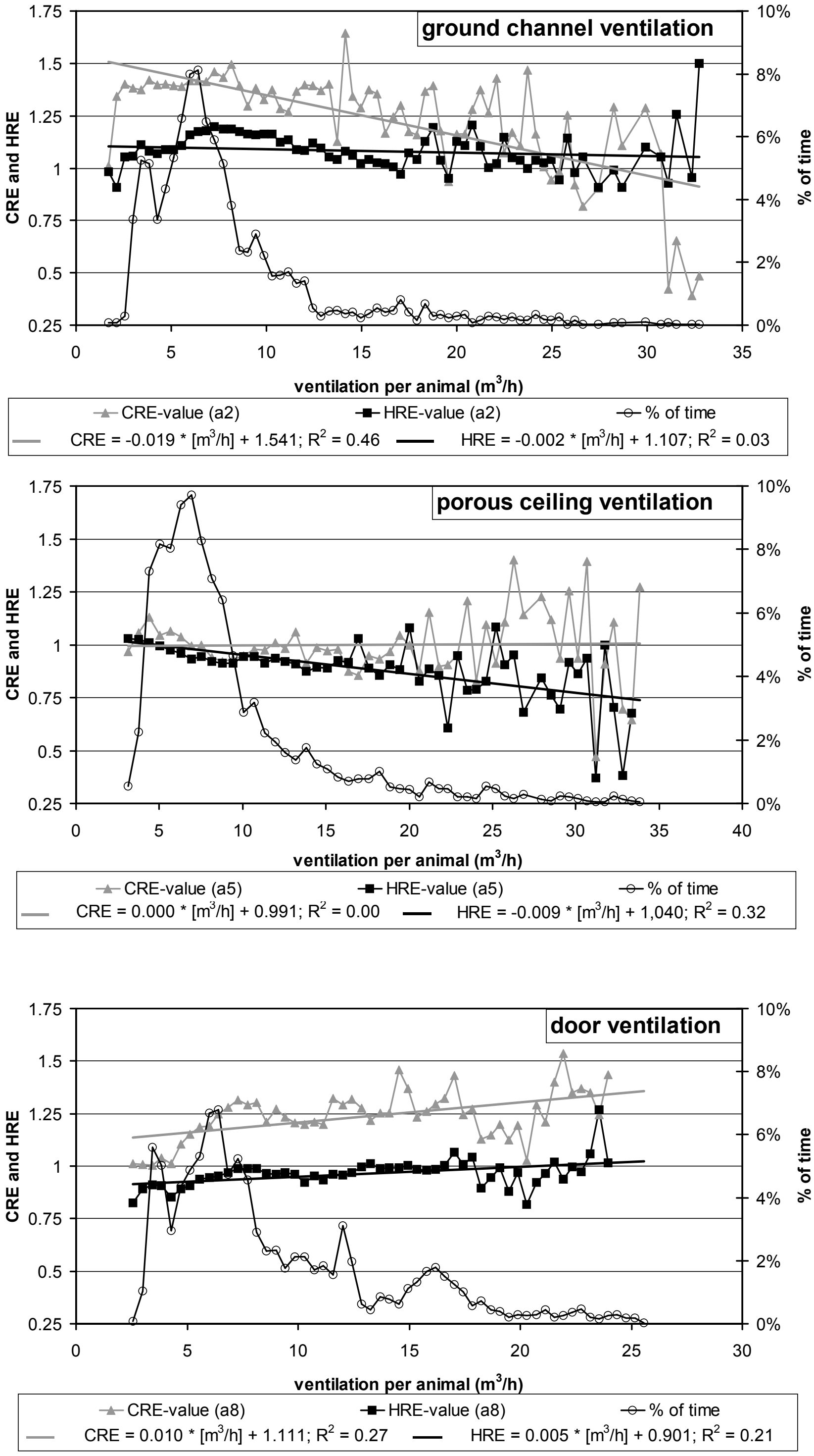

Figure 2. Effect of ventilation rate on the value of CRE and HRE at the automatic sampling points and frequency distribution of ventilation rate in the three experimental rooms.

Discussion

There were differences in CRE and HRE among the three experimental rooms. The room with ground channel ventilation showed the highest value of CRE and HRE and the lowest CO_2 concentration in the AOZ (table 4), even while this room had the highest inlet concentration (table 2). Similar results were found by Aarnink and Wagemans (1997), who compared a room with ground channel ventilation and a low outlet with a room with porous ceiling ventilation and a high outlet. Ground channel ventilation showed better air quality in the AOZ. The results of Breum et al. (1990) also indicated that ventilation systems in a pig facility with a low air inlet and a high air outlet, and thus an upward airflow, gave more effective ventilation than a downward flow.

Ventilation system design has an effect on the air quality in the AOZ. A high CRE, resulting in lower contaminant concentrations under cold conditions with minimal ventilation, and a high HRE, resulting in lower temperatures under warm conditions with high ventilation rates, are expected to improve animal performance and animal welfare. This was not determined in the research because the experimental design was not suitable for this. Ongoing research focuses on this topic.

The values of CRE and HRE are not solely dependent on ventilation system design. One very important factor is the measurement location, as illustrated by comparison of the results from the different sampling points in each room. The average CRE and HRE values in the AOZ would give a better impression of the effectiveness of the air displacement, but it is difficult to measure CO_2 concentrations in the AOZ.

Systems with high values of CRE and HRE, indicating effective ventilation in the AOZ, can use lower ventilation rates. This can be illustrated by the climate settings used in this research (table 1): the ventilation settings used in the room with ground channel and door-ventilation were lower than in the room with porous ceiling ventilation. This can be an important aspect in reducing costs for air scrubbing, which is one way to reduce emissions from livestock facilities effectively.

Effective ventilation can be realized by locating the air inlet close to the AOZ. This might increase the risk for high air velocities, or drafts, in the AOZ. Air quality and thermal comfort are both important factors in creating a healthy microclimate and preventing problems with animal health, animal welfare, and sub-optimal production. To evaluate the performance of a ventilation system, the measurements should include draft measurements, and the sampling points should be located in such a way that they give information about the entire AOZ. A possible strategy for choosing the measurement locations is to carry out a preliminary study in the experimental room, in which one permanent sampling location is chosen close to the lying area of the animals and a movable set of sensors is used at several other sampling locations. Comparing the simultaneous measurements from the reference location and the other sampling locations should provide information on the variation within a pen and on the representativeness of the reference location chosen.

Conclusions

- Ground channel ventilation provided more fresh air in the AOZ than door-ventilation and porous ceiling ventilation for this test.
- CRE depends on the location of the sampling point. This is caused by the airflow pattern but also by the number of animals (as sources of CO_2 and heat) near the sampling point.
- The CRE and HRE values can be different at one sampling point in the AOZ.
- For ground channel ventilation and for door-ventilation, CRE was affected by the ventilation rate, which is greatly affected by animal age, animal weight, and outside temperature. For ground channel ventilation in the tested setup, CRE decreased with increasing ventilation. For door-ventilation, CRE increased with increasing ventilation because the sampling point was in the back of the room. In the room with porous ceiling ventilation, CRE was greatly affected by the lying behavior of the animals, and there was a slight decrease in CRE with increasing ventilation.

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CHAPTER 3

Measurement of Air Velocity in Animal Occupied Zones Using an Ultrasonic Anemometer

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Abstract

The air velocity in the animal occupied zone (AOZ) of a pig facility influences the thermal comfort of pigs and is affected by the ventilation system in the building. Little is known about the relationship between the air velocity in the AOZ and the ventilation system design. This article describes the development and a practical test of an air velocity measuring system in the AOZ using ultrasonic anemometers.

The anemometers were protected by a wire protection cage, which resulted in a lower air velocity measurement that was corrected by a linear correction factor of 0.83. A suitable aggregation interval for time-averaged air velocity measurements in occupied pens was 300 s. The effect of animal activity on the measured air velocity was minimal and therefore neglected, but the location of the anemometer in a pen was deemed important. A representative location was above the resting place of the animals over the solid floor. The presence of an anemometer in a pen resulted in some minor changes in the lying behavior of the animals.

In the experimental door-ventilated room with weaned piglets there was a clear (0.04 m/s) and significant difference in average air velocity between pens 3 and 9 ($P < 0.001$). The maximum air velocity of 0.15 m/s advised was exceeded in 21% of the time a pen in the back of the room. In a pen closer to the door, air velocities appeared to be too high for less than 2% of the time.

The measuring system described in this article can be combined with air quality and temperature measurements in the AOZ for determination of the performance of ventilation systems and comparison of ventilation systems.

Keywords. Air velocity, Ventilation system, Pig facilities.

Introduction

Air velocity in the animal occupied zone (AOZ) of a pig facility influences thermal comfort, behavior, and production of pigs. Therefore, air velocity in the AOZ in livestock buildings is one important aspect of the building performance (Zhang et al., 2001). Several ventilation systems are commonly used in pig rooms. Fresh air supply to the AOZ depends on the ventilation system design (Van Wagenberg and Smolders, 2002). However, little is known about the relationship between the ventilation system design and the air velocity in the AOZ. Only some experimental data are available. One experiment with simulated pigs showed that for ventilation systems with a high slot-inlet, the air velocity in the inlet is an important factor for the air velocity in the AOZ, especially under warm summer conditions (Randall, 1980). A slot ventilated building with the air inlet located in the sidewall affected air velocity in the AOZ along with inlet height and distance from the inlet (Hoff, 1995). No experimental data are available on air velocities in the AOZ under practical conditions with occupied pig rooms or with other ventilation system designs.

Airflow patterns and air velocity distribution in rooms with different ventilation systems can be predicted by numerical simulation models as long as it considers empty test rooms without obstacles (Harral and Boon, 1997; Bjerg et al., 1999). Both numerical simulations and lab measurements show that the effect of pen partitions and simulated animals in rooms reduce the air velocity in the AOZ compared to an empty room (Bjerg et al., 2000). The complex environment of an occupied pig room where animal presence and animal activity significantly affect airflow pattern characteristics has not been simulated yet (Smith et al., 1999).

For determination of the performance of a ventilation system as part of building performance, the quality of the climate in the AOZ is an important factor, besides other factors, such as energy consumption and operational costs. Quality of the climate in the AOZ can be characterized by air quality variables, such as contaminant concentrations, and variables affecting thermal comfort, for example air temperature and air velocity. Contaminant concentration and temperature measuring systems are available and have been reported in literature (Aarnink and Wagemans, 1997; Van Wagenberg and Smolders, 2002).

Several sensor types are available to measure air velocity, but not all sensor types can be used under practical conditions in occupied pig rooms. Some sensors are impractical in swine houses, due to the expected low air velocities in the AOZ, the presence of ammonia, and/or possible dust deposition on the sensor. An ultrasonic anemometer is a suitable sensor for measuring air velocity in the AOZ. In this study, a measuring system with this sensor type has been tested under practical conditions and a procedure for data processing is proposed. At the same time the system was used to gain insight into occurring air velocities in the AOZ in a door-ventilated room for weaned piglets, the animal category that is the most sensitive to discomfort in indoor climate.

Objective

The objective of this research was manifold. The first objective was testing the measuring system, which consisted of determining the effect of a wire protection cage around the anemometer. The second objective concerned data processing, and dealt with determining of the best suitable aggregation interval for time-averaged air velocity measurements and determining turbulence intensity. The third objective was related to the use of the anemometer in an occupied pig pen and was subdivided into: determining the effect of pig activity on the air velocity measured; determining the effect of the location of the anemometer in a pen on the measured air velocity; determining the effect of presence of an anemometer in a pen on the resting locations of the animals; and using the measuring system during one batch in a door-ventilated room for weaned piglets (in two pens).

Material and Methods

Anemometers and Effect of Wire Cage

Air velocity measurements were performed with ultrasonic anemometers (Gill, Windmaster 1086M), which each consisted of three acoustic transmitters and three acoustic receivers at 0.11 m distance. The speed of propagation of sound from the transmitter to the receiver depended on the one-dimensional air velocity between the transmitter and the transducer. The anemometers measured three one-dimensional air velocities, which were components of the omnidirectonal air velocity. The total height of the anemometers was 0.75 m and the diameter of the construction that holds the transmitters and receivers was 0.24 m. The measuring range was 0 to 45 m/s, the resolution was 0.01 m/s, and the accuracy for the omnidirectional air

velocity was ±0.01 m/s (stated by the manufacturer). The maximum measuring frequency was 1 Hz. Because the deviation could vary per sample, averaging air velocities over many samples reduced the chance of over or underestimation of the air velocity.
A wire cage (fig. 1) protected the anemometers. The openings in the cage were 20 × 20 mm, and the steel wire was 2.5 mm in diameter. The height of the cage was 0.77 m and the diameter was 0.27 m. The anemometer was mounted in the cage such that there was a space of 20 mm between the anemometer and the bottom of the cage.

Figure 1. Air velocity anemometer in a wire cage in the middle of the pen.

To determine the effect of the wire cage under different flow directions an anemometer was placed in a wind tunnel in two positions, and air velocity in the wind tunnel was varied stepwise between 0 and 2 m/s. During each step (500 s) air velocity was measured with and without the cage. Measurements were done with the anemometer placed perpendicularly (90°) on the z-direction of the airflow and with the anemometer placed at an angle of 40° of the z-direction of the airflow (fig. 2). These positions were chosen because it was expected that in the AOZ most of the airflow would vary between these directions. The effect of the cage on the turbulence intensity was also determined. Turbulence intensity (I_t) was defined as the standard deviation of the average omnidirectional air velocity divided by the average omnidirectional air velocity (Smith et al., 1999).

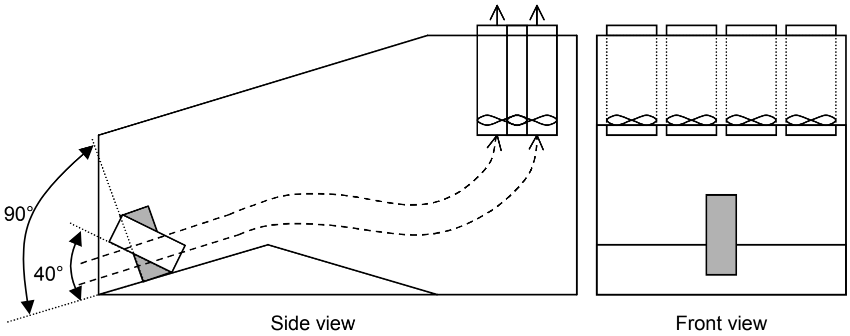

Figure 2. Anemometer positions in the wind tunnel experiment (- - -> = airflow).

Description of Room

The experiments were carried out in one room for weaned piglets at the experimental farm in Raalte in The Netherlands. The room was designed for housing of piglets from 7 kg of bodyweight to about 23 kg. Then they were moved to a finishing room. The room was door-ventilated, and built as a representative copy of actual door-ventilated rooms.

Figure 3 shows a plan and a cross-section of the room. The room had five pens (for nine animals each) on each side of the operator walkway. In the pens 50% of the floor was solid wood with a spherical shape and floor heating, and 50% was a metal tribar slatted floor. At the front of the pen there was a water channel of 0.40 m. Feed was supplied in a dry feeder, water in a separate drinker. Ventilation air entered the room from the central alley, where the air was preheated up to 5°C. Through an opening in the door (0.58 × 0.92 m) the air entered the room and flowed over the operator walkway to the back of the room (door-ventilation). Air was removed from the room by a ventilator in a ventilation shaft, directly behind the door at a height of 2.10 m. In the ventilation shaft an automatic valve and a measuring fan were placed for controlling the ventilation rate. Control of ventilation was based on the inside temperature and on the settings in the climate controller (table 1). Heating in the room was available by a hot water pipe mounted against the surrounding walls and a radiator in the back of the operator walkway. Lights were on in the room between 6:00 A.M. and 4:00 P.M. (unless differently stated). The pens in the compartment were numbered according to figure 3.

In rooms with door-ventilation, air distribution over the pens was uneven (Van Wagenberg and Smolders, 2002). At higher ventilation rates air flows over the operator walkway to the back of the room before it flowed over the pen partition. Much of the fresh air entered the pens in the back of the room, resulting in effective removal of contaminants and heat from

these pens, but increasing the risk for high air velocities. Toward the front of the room there was less fresh air supply and possibly lower air velocities.
Fresh air entered the pens from the operator walkway; in the pens the airflow was expected to be directed towards the back of the pen. Due to heat production in the pen (animals, floor heating) air will rise and less fresh air will reach the back of the pen.

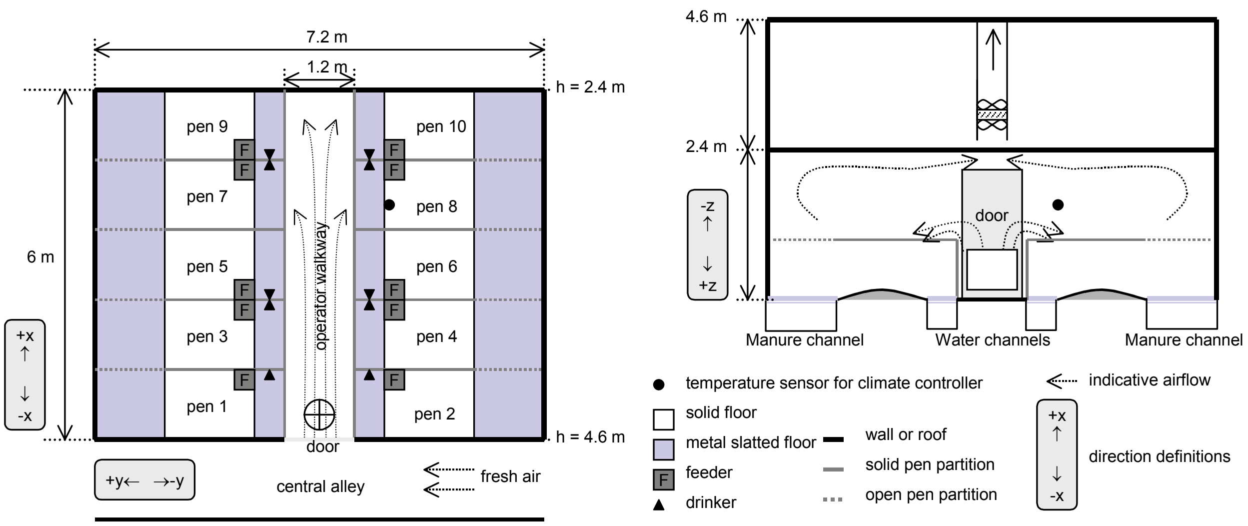

Figure 3. Plan and cross-section of compartment for weaned piglets (h = height).

Table 1. Climate settings in room.

Day No.	Temperature (°C)			Ventilation per Piglet (m^3/h) [a]	
	Heating	Floor Heating	Setting Point Ventilation	Minimum	Maximum
2	28	40	30	4	10
4	25	40	27	4	11
8	24	35	26	5	13
21	18	25	21	5	20
28	18	25	21	6	25
49	17	20	20	6	25

[a] Temperature range between minimum and maximum ventilation 4°C.

Measurements in the Room

After testing the measuring system in the wind tunnel the anemometers were placed at different locations in pens 3 and 9 of the experimental room. These two pens were selected because they were positioned on one side of the operator walkway and because it would give insight into the expected differences in microclimate between a pen at the front and at the back of the room. Possible anemometer locations within the pens were defined and numbered as indicated in figure 4. The letter a indicates that no specific number in the location notation is meant. In pen 3 the feeder was placed in zone 1-3-a, in pen 9 the feeder was placed in zone 1-1-a. Details on the measuring time and location are addressed later in this article.
Ventilation rate was measured with a measuring fan in the ventilation shaft (accuracy < 50 m^3/h) and recorded every 15 min. Outside temperature, temperature of the floor heating water, and room air temperature (location indicated in fig. 3) were recorded every 15 min.
Animal behavior was recorded with a video system and analyzed later. Details on the recording time, frequency, and animal behavior categories are described later in this article.

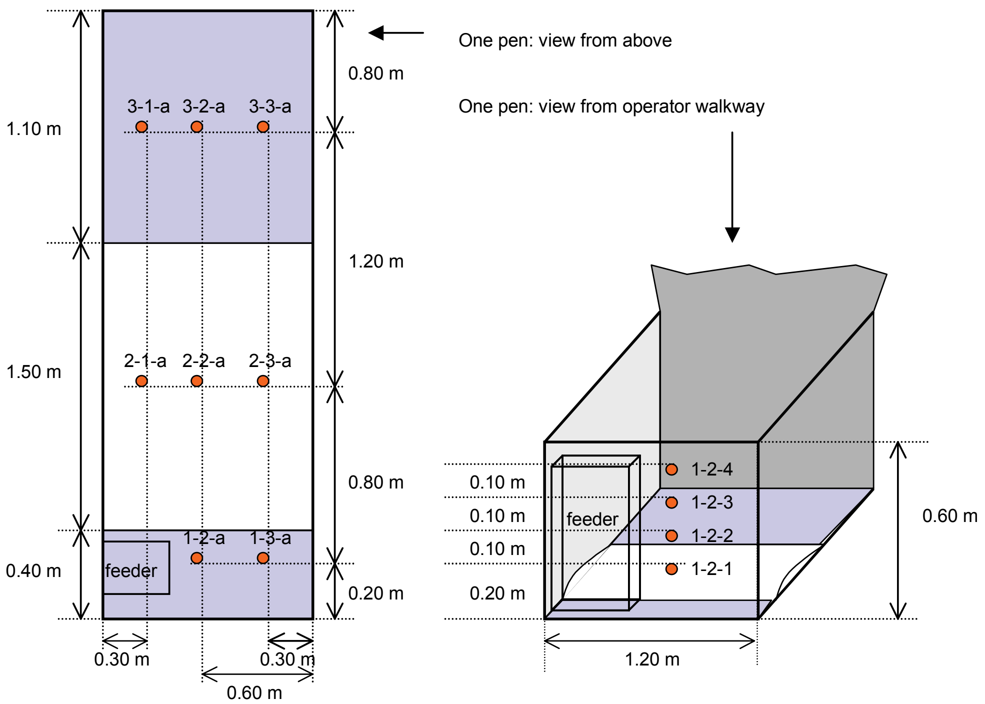

Figure 4. Zones within a pen and the notation of the different anemometer locations in the pen. The letter "a" indicates that no specific number in the location notation is meant.

Aggregation Interval and Turbulence Intensity

Air velocity was measured with a 1-Hz sample frequency. This smallest possible sample interval (with the anemometer used) was chosen to take the smallest turbulences into account in the measurements. To get workable data files over long-term measurements, for example during one batch of weaned piglets, aggregation to time averaged air velocities is necessary. For determination of the most suitable aggregation interval, two analysis methods were used for three air velocity data sets. The data sets were collected at daytime, with the anemometer located at location 2-2-2.

For the first analysis method the air velocity signals were aggregated over 60-s intervals. Fourier analysis (Jenkins and Watts, 1969) was used for the original as well as for the aggregated data. Let N the number of recordings or aggregates be even, i.e. N = 2*n*. The signal was written as a finite Fourier series, i.e. weighted sum of first up to *n*th harmonic functions, such that the finite Fourier series coincided with the velocities observed at the measuring points. By computing and plotting the percentage of variance accounted for by the first up to *j*th (*j* = 1 . . . *n*) harmonic function against the harmonic function cycle length, the impact of harmonic functions was displayed. The plot was used to decide which higher order harmonic functions could be ignored. A suitable aggregation interval was based on the lowest order harmonic function to be ignored. The analysis was performed using the software package Genstat (1993).

In the second analysis the directional air velocities (x, y, and z) of the three data sets were aggregated over several intervals DT, between 2 and 600 s. The time averaged omnidirectional air velocity was calculated as the root mean square (RMS) using equation 1.

$$U_{DT} = \sqrt{(\overline{x_{DT}})^2 + (\overline{y_{DT}})^2 + (\overline{z_{DT}})^2} \quad \textbf{(1)}$$

where x_{DT}, y_{DT}, and z_{DT} are the time averaged directional air velocities over an aggregation interval DT (s), resulting in a time averaged omnidirectional air velocity U_{DT}. The second analysis was carried out because it was expected that the value of U_{DT} would decrease with increasing aggregation interval DT. Changes in airflow direction within interval DT would result in lower values for x_{DT}, y_{DT}, and z_{DT}, and therefore in lower U_{DT}. By plotting U_{DT} against the aggregation interval DT, this effect was shown.

The three original data sets were also used to calculate turbulence intensity I_t in the AOZ.

Effect of Pig Activity on Anemometer Measurements

It was expected that pig activity would result in higher momentary values for air velocity. This effect was determined using air velocity measurements (1-Hz sample frequency) and animal activity observations. These measurements were done simultaneously in pen 3, during a period of 2 h, between 11:30 A.M. and 1:30 P.M. (data set 1 in table 3). Animal activity was recorded continuously. The recordings were analyzed and the momentary values of the air velocity were linked to one of the six defined categories for pig activity: no contact between pig and anemometer cage; pig sniffing the anemometer cage; pig rubbing against the anemometer cage; pig lying under anemometer cage; pig running in pen; pig bumping against anemometer cage.

Effect of Location in Pen on Air Velocity, Airflow Direction

It was expected that there would be heterogeneity in air velocity and airflow direction within a pen. To quantify this heterogeneity, one reference anemometer was located at location 2-2-2, and another movable anemometer was located at one of the other 28 sampling locations (fig. 4). The location of the reference anemometer was chosen to be close to the resting area of the animals, but in such way that the floor area under the cage was still accessible for the animals. Measurements with both anemometers started simultaneously and lasted 15 min (sample frequency 1 Hz, aggregation interval 300 s). After this period the movable anemometer was placed in another location. The average air velocity and airflow direction in both the reference location and the other sampling location were determined, as well as the difference in air velocity between the two locations. The experiment was carried out in pens 3 and 9, both with eight animals with low weight in the pen (an average weight of 8 kg) and with eight heavier animals (an average weight of 20 kg). The ventilation rates during the experiments are presented in the results section.

Air velocity values in the front (zone 1-a-a) in the middle (zone 2-a-a) and in the back (zone 3-a-a) of the pen were compared using two-sample t-tests. The representatives of the reference anemometer was determined by comparing average air velocity values per zone (1-a-a, 2-a-a, and 3-a-a) with the air velocity at the reference location using two-sample t-tests.

Effect of Presence Anemometer on Resting Locations of the Piglets

At location 2-2-2, the bottom of the wire cage was located 0.20 m above the solid floor (measuring height 0.30 m). This presence of the cage might affect the resting locations of the piglets in the pen. Resting locations were analyzed to assess this possible effect. During one batch, two periods were analyzed during which the lights were on continuously. The first period was from days 1 to 11 in the batch (light animals) and the second period was from days 29 through 34 (heavy animals). Each hour a video picture was recorded of pens 1 and 3 and pens 7 and 9 (24 hours per day). The pictures were analyzed as to percentage of the animals standing and resting on the slats above the manure channel and in the rest of the pen. Pens 1 and 3 were compared, as well as pens 7 and 9 using a two-sample t-test.

Air Velocity in AOZ during Batch

The air velocity in pens 3 and 9 was measured continuously during one batch, except for the first week of the batch (20 February until 28 March 2002). Experimental conditions are shown in table 2. The anemometers were in both pens located at location 2-2-2 (1 Hz, sample frequency, 300-s aggregation interval). Air velocities were plotted against day number and ventilation rate. Air velocities in pens 3 and 9 were compared using a two-sample t-test.

Table 2. Experimental conditions during batch with air velocity measurements in AOZ (period 20 February – 28 March 2002).

	Floor Temperature (°C)	Room Temperature (°C)	Ventilation (m^3/h)
Minimum	26.8	20.2	450
Average	29.6	22.4	576
Maximum	43.0	25.0	1263

Results and Discussion

Effect of Wire Cage

The effects of the wire cage on the wind tunnel measurements are presented in figure 5. The air velocity in the wind tunnel was in most cases higher than the expected measuring range in a pigpen. The effect of the cage for low air velocities in the wind tunnel (lower than 0.5 m/s) proved to be equal to the effect of the cage for the higher air velocities (using a two-sample t-test). This result indicates that, in the air velocity range tested, the air velocity did not influence the effect of the cage.

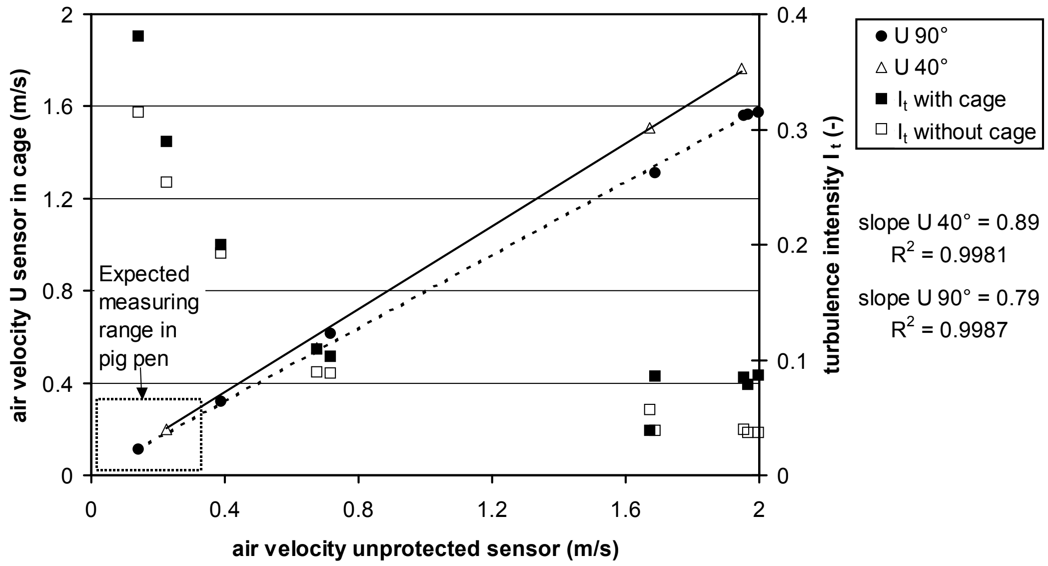

Figure 5. Effect of wire cage on turbulence intensity and on air velocity measured in wind tunnel with two anemometer positions.

There was linearity between the air velocity measured by the unprotected and the protected anemometer. For the 90° position, the ratio was 0.79, for the 40° position, the ratio was 0.89. The difference in ratio between the two positions indicates that the effect of the cage on the air velocity depends on the direction of the airflow and proved to be significant using a two-sample t-test ($P < 0.001$). However, considering the relatively small difference and the expected measuring range, only one omnidirectional correction factor was used. This factor was 0.83, the average ratio between the air velocity in the wire cage and the air velocity around the wire cage in the wind tunnel measurements. A direction-dependency for this correction factor was not expected to increase the reliability of the air velocity measurements in the AOZ.

Turbulence intensity [(Std.dev.U_{DT})/U_{DT}] was increased by 10% to 20% by using a cage around the anemometer. This result was unexpected, since Smith et al. (1999) found that there was a small reduction in turbulence when an anemometer was placed in a wire cage. The different effects can be due to the differences in cage construction.

Aggregation Interval and Turbulence Intensity

Characteristics of the three datasets used to determine the most suitable aggregation interval and the turbulence intensity are presented in table 3. The result of the Fourier analyses as to the three data sets is shown in figure 6. There are four graphs, for the three directions and the omnidirectional air velocity signal. The cycle length of the harmonic function contributing to the signal is on the horizontal axis and the percent of variance accounted for by the harmonic function with cycle length equal to or bigger than *t* (*t* in seconds) is on the vertical axis.

Table 3. Characteristics of the three data sets used for the Fourier analyses, aggregation analyses, and determination of turbulence intensities. [a]

Data Set	Pen No.	Average Animal Weight (kg)	Average Ventilation Rate (m^3/h)	No. of Air Velocity Recordings (N)	Average Air Velocity (m/s)			
					X	Y	Z	Omni. Dir
1	3	14	1497 (106)	7600	0.04	0.07	0.06	0.11 (0.04)
2	3	11	702 (22)	5842	0.02	0.05	-0.01	0.08 (0.03)
3	9	11	702 (22)	5842	-0.01	0.14	0.03	0.16 (0.05)

[a] SD in parentheses.

The harmonic functions contribute to 100% of the variance in the signal when the cycle length of the function equals 2 × DT , what is logical because aggregating the signal filters out harmonics with a shorter cycle length. In the y-direction and in the z-direction for data set 1 a relatively large percentage of variance in the signal consists of harmonic functions with a cycle length of more than 1000 s. For data sets 2 and 3 in the x-and z-direction, what is clear at cycle length of 400 s. This effect can be caused by the delay in the ventilation control, assuming that ventilation rate and air velocity in the AOZ are related. The delay in ventilation control is determined by the time constant of the temperature sensor used. This sensor was mounted in a small metal tube (by the manufacturer). It takes some time for the sensor to register a temperature change. To include this effect a suitable aggregation interval is shorter than 400 s. Based on these results an aggregation interval of 300 s and a measuring frequency of 1 Hz were adequate for the level of turbulence encountered. The recorded average air velocity per direction (x, y, z) was used to determine the omnidirectional air velocity for the 300-s interval. This aggregation interval is a quarter of the interval used by Smith et al. (1999) for handling air velocity measurements in AOZ; animal weight in that experiment was 40 kg. Hoff (1995) used an aggregation interval of 180 s for an unoccupied test room.

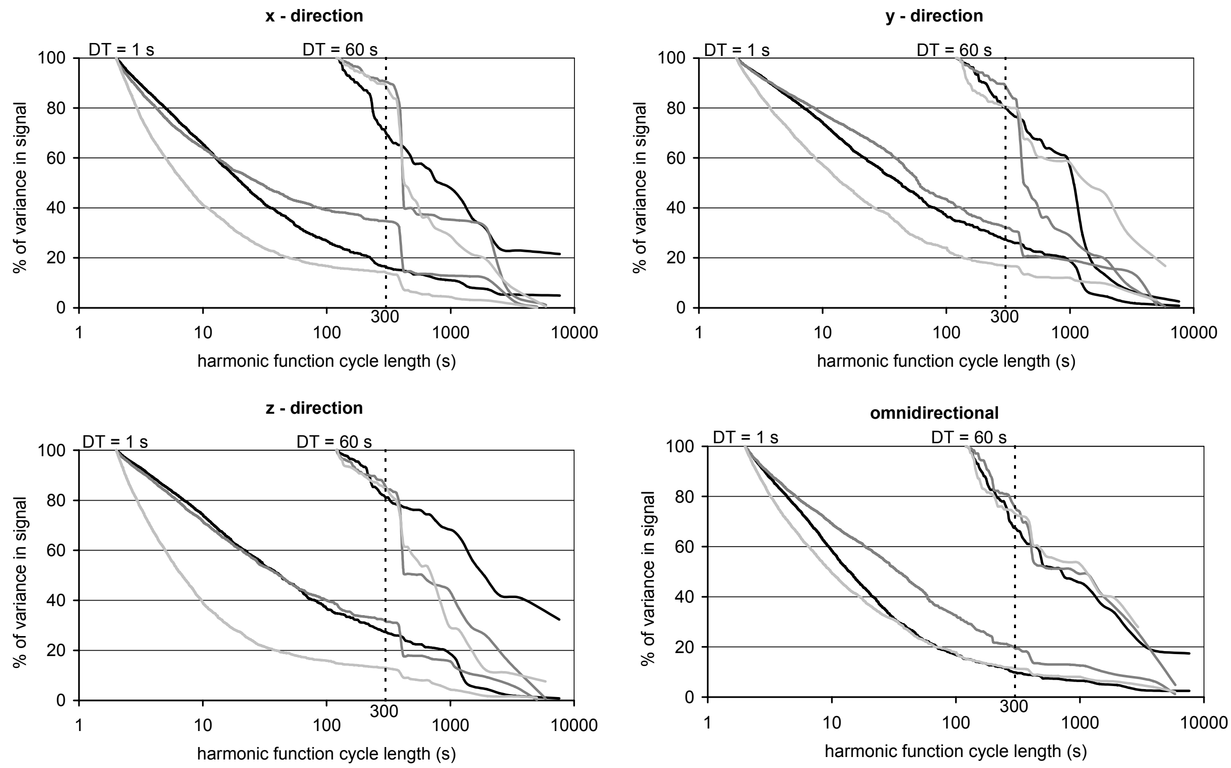

Figure 6. Result of Fourier analyses of three data sets (▬data set 1, ▬data set 2, ▬data set 3) per direction and omnidirectional for the non aggregated data (DT = 1 s) and aggregated data (DT = 60 s); on the horizontal axis the cycle length of the harmonic function (t) and on the vertical axis the percent of variance accounted for by the harmonic function with cycle length equal to or bigger than t s.

Figure 7 shows the effect of the length of the aggregation interval (DT) on the omnidirectional air velocity. For all three datasets the omnidirectional air velocity is reduced by increasing the aggregation interval DT from 1 and 100 s. Data set 1 demonstrates the greatest effect. At a 300-s aggregation interval, the air velocity seems to be stable for all three data sets, which indicates that the measurements will show the net airflow at the measurement location. Turbulence intensity [(Std.dev.U_{DT})/U_{DT}] was 0.41 for data set 1, 0.44 for data set 2, and 0.34 for data set 3. These values are of the same magnitude as the values found by Smith et al. (1999) in occupied pigpens.

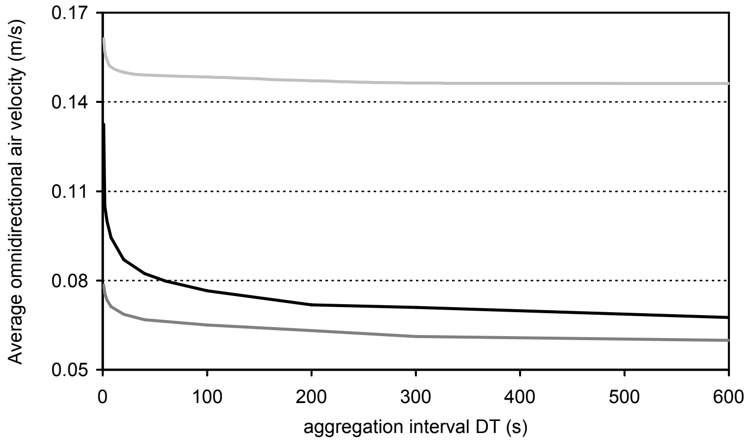

Figure 7. Effect of aggregation interval DT on average omnidirectional air velocity for three data sets (▬ data set 1, ▬ data set 2, ▬ data set 3).

Although there are indications that quick fluctuating airflow, or turbulence, causes an unpleasant feeling for the piglets (Smith et al., 1999), turbulence measures were not pursued further for two reasons. First, the dataloggers were not able to process the data before storing, and at a 1-Hz store frequency the memory capacity was less than 1 day. Second, it was not known what the appropriate sample and aggregation interval was for calculation turbulence such that it was the best indicator for thermal comfort of piglets.

Table 4. Effect of pig activity on the momentary air velocity in pen 3 with pigs of 14.5 kg. [a]

Kind of Interaction between Pig and Anemometer	Duration (s)	% of Time	Avg. Momentary Air Velocity (m/s)
No contact	7709	71	0.11 (0.04)
Sniffing	872	8	0.13 (0.06)
Rubbing	112	1	0.11 (0.05)
Lying under anemometer	1758	16	0.11 (0.04)
Running in pen	280	3	0.13 (0.05)
Bumping against anemometer	55	1	0.12 (0.05)

[a] SD in parentheses.

Effect of Pig Activity on Anemometer Measurements

Pig activity had minor effect on the average momentary air velocity (table 4). In the 2-h observation period during daytime, when most activity was expected, 71% of the time there was no contact between the pigs and the anemometer. The effect of the small air velocity increase, only 29% of the time, was minimal. A statistical analysis of the differences as well as correction of the measured air velocity for this interaction was considered to be unnecessary.

Effect of Location in Pen on Air Velocity and Airflow Direction

The impact of location on the measurements is shown (table 5) with values averaged over 15 min and 8 (1-a-a and 2-a-a) or 12 (3-a-a) anemometer locations. Positive and negative values in table 5 refer to the airflow direction (fig. 3). The SD was determined using the average air velocities at the locations.

Table 5. Directional ($\bar{x}$, $\bar{y}$, $\bar{z}$) and omnidirectional air velocity (U) at different locations within pens 3 and 9 with light and heavy animals.[a]

		Air Velocity (m/s)			
		$\bar{x}$	$\bar{y}$	$\bar{z}$	U[b]
Pen 3 light	Front (1-a-a)	0.00 (0.01)	0.03 (0.04)	0.01 (0.01)	0.04 (0.03)^{a}
	Middle (2-a-a)	0.01 (0.01)	0.01 (0.04)	-0.01 (0.02)	0.04 (0.02)^{a}
	Back (3-a-a)	0.00 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)^{b}
Pen 3 leavy	Front (1-a-a)	-0.01 (0.02)	0.05 (0.02)	0.01 (0.02)	0.05 (0.02)
	Middle (2-a-a)	0.01 (0.01)	-0.01 (0.03)	-0.02 (0.02)	0.04 (0.02)
	Back (3-a-a)	-0.04 (0.02)	-0.01 (0.02)	-0.01 (0.02)	0.05 (0.02)
Pen 9 light	Front (1-a-a)	0.00 (0.01)	0.03 (0.03)	0.00 (0.01)	0.04 (0.03)^{ab}
	Middle (2-a-a)	-0.04 (0.01)	0.03 (0.03)	-0.01 (0.01)	0.05 (0.02)^{a}
	Back (3-a-a)	-0.01 (0.01)	0.00 (0.01)	0.00 (0.01)	0.02 (0.01)^{b}
Pen 9 heavy	Front (1-a-a)	-0.03 (0.02)	0.04 (0.02)	-0.01 (0.01)	0.06 (0.02)^{c}
	Middle (2-a-a)	-0.08 (0.02)	0.05 (0.02)	-0.02 (0.03)	0.10 (0.02)^{d}
	Back (3-a-a)	-0.01 (0.01)	0.00 (0.01)	-0.02 (0.01)	0.02 (0.01)^{e}

[a] SD in parentheses.
[b] different letters indicate a significant difference in air velocity between front, middle and back of the pen (^{a,b} =P < 0.05; ^{d,e,c} = P < 0.001)

At the front of pen 3 at the locations 1-a-a (especially 1-1-1 and 1-2-1) air velocity was relatively high in the y-direction, air flowed from the front to the back of the pen close to the floor. Air velocities in the x and z-directions were lower at the front of the pen. At the back of the pen with light animals, air velocity was very low in all directions. With heavy animals airflow was directed towards the door at the back of the pen (direction –x).
At the front of pen 9 airflow was directed towards the back of the pen, in the y-direction. In the middle of the pen the airflow direction was strongest in the x-direction toward the door,

especially with heavy animals. At the back of the pen air velocities in all directions were relatively low.

Table 6. Average difference in air velocity between location 2-2-2 in the pen and other zones in the pen, for pens 3 and 9 with light and heavy animals.[a]

	Ventilation Range (m^3/h)	Average Difference in Air Velocity (m/s) [b]		
		Front (1-a-a)	Middle (2-a-a)	Back (3-a-a)
Pen 3 light	340 – 460	-0.01 (0.04)	0.01 (0.02)	-0.01 (0.01)^a
Pen 3 heavy	550 – 1370	0.03 (0.02)^a	-0.01 (0.02)	-0.01 (0.03)
Pen 9 light	440 – 490	0.01 (0.04)	0.00 (0.03)	-0.05 (0.02)^b
Pen 9 heavy	620 – 740	-0.05 (0.02)^b	-0.02 (0.03)	-0.07 (0.02)^b

[a] SD in parentheses.

[b] different letters indicate a significant difference in air velocity between the reference location 2-2-2 and the front, middle or back of the pen (^{a} = $P < 0.01$; ^{b} = $P < 0.001$).

In table 6 the average differences in air velocity among zones in the pen (front, middle, and back) and location 2-2-2 are shown. Negative values in table 6 mean that the air velocity at location 2-2-2 is higher; positive values the reverse. The results show that even in the small pens used in this research, there were significant differences within the pen sometimes up to 0.07 m/s (pen 9, heavy animals). The air velocity was lowest at the back of pen 9, above the slats. With heavy animals, also the air velocity at the front pen 9 was lower than at location 2-2-2. This may be explained by fresh air entering the pen from the operator walkway, then flowing over the pen partition and falling on the slats at the front of the pen without reaching the anemometer that was located 0.20 m behind the pen partition. The airflow was then directed to the back of the pen, resulting is some upward flow caused by obstruction of the pigs and heat produced in the resting area. This airflow pattern resulted in a comparatively higher air velocity at the locations 2-a-a. In pen 3 the fresh airflow from the operator walkway was smaller, and therefore the differences in air velocity within the pen were smaller.

It is impractical to locate anemometers at several locations in one pen, so one *best suitable* location should be chosen. Table 6 shows that the air velocity measured at location 2-2-2 shows no significant differences in air velocity with the space-average air velocity in the middle of the pen (2-a-a) above the resting area. Therefore location 2-2-2 was chosen as the standard measurement location.

Effect of Presence of Anemometer on Resting Locations of the Piglets

Results of the comparison of the resting locations in pens 1 and 3, and pens 7 and 9 are presented in table 7. In this experiment there was a possibility of interactions of the pen-effect with the anemometer presence-effect. Changes in percentage of animals lying on the solid floor were considered to have the largest effect in animal welfare and animal production. For light animals, there was no significant difference. For heavy animals there was some difference (9% between pens 7 and 9), what can be explained by the fact that it was more difficult for heavy animals to use the floor area under the sensor. However, the significant differences were relatively small and the general pattern did not change. It can be concluded that measuring air velocity in the AOZ results in minor changes in resting locations in the pen.

Table 7. Average percent of animals lying and standing on the solid floor/water channel and on the slats in pens with and without anemometer. [a]

	Pen 1	Pen 3	Pen 7	Pen 9
Presence of anemometer	No	Yes	No	Yes
Day 1 to 11 light animals				
Lying on solid floor or water channel	76	80	84	78
Standing on solid floor or water channel	15	14	11^b	18^b
Lying on slats	0	0	0	0
Standing on slats	9^a	6^a	5	5
Day 29 to 34 heavy animals				
Lying on solid floor or water channel	67	65	75^c	66^c
Standing on solid floor or water channel	12	12	11^a	17^a
Lying on slats	11^c	16^c	6	9
Standing on slats	9	8	8	9

[a] letters indicate a significant difference (^{a} = P < 0.05; ^{b} = P< 0.001; ^{c} = P< 0.01)

Air Velocity in AOZ

The air velocity in pens 3 and 9 was measured during one batch (except for first week). In figure 8 the course of the daily average air velocity is shown. The air velocity measured in pen 9 was higher than in pen 3. During the batch the air velocity increased in both pens, but not in proportion to the ventilation rate. During the period 20 February to 6 March 2002 there was only a minor increase in daily average ventilation, but there was an important increase in air velocity in the pens. Most of the time the air velocities in both pens show the same fluctuations, but on day 9 March 2002, the air velocity in pen 9 was relatively low, while in pen 3 the air velocity was relatively high.

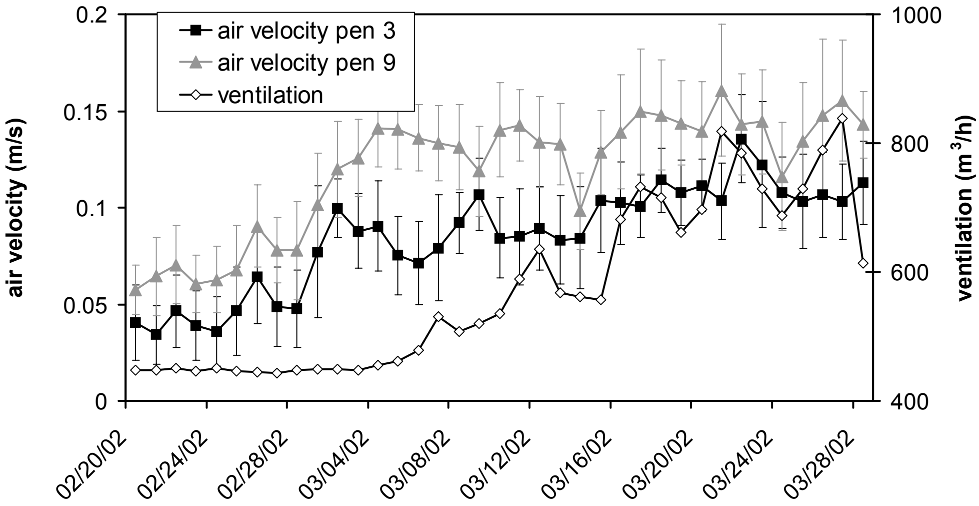

Figure 8. Daily average ventilation and air velocity (range indicates standard deviation) at location 2-2-2 in pen 3 and pen 9 during one batch (except for first week) of weaned piglets in experimental room.

In figure 9 the air velocity measured is plotted against ventilation rate. Higher ventilation rates increase the air velocity, especially in pen 9. At low ventilation rates (between 400 and 600 m^3/h) there is much variation in air velocity in both pens. The analysis of the air velocities during the batch as presented in figure 8 and 9 cannot explain all the variation encountered.

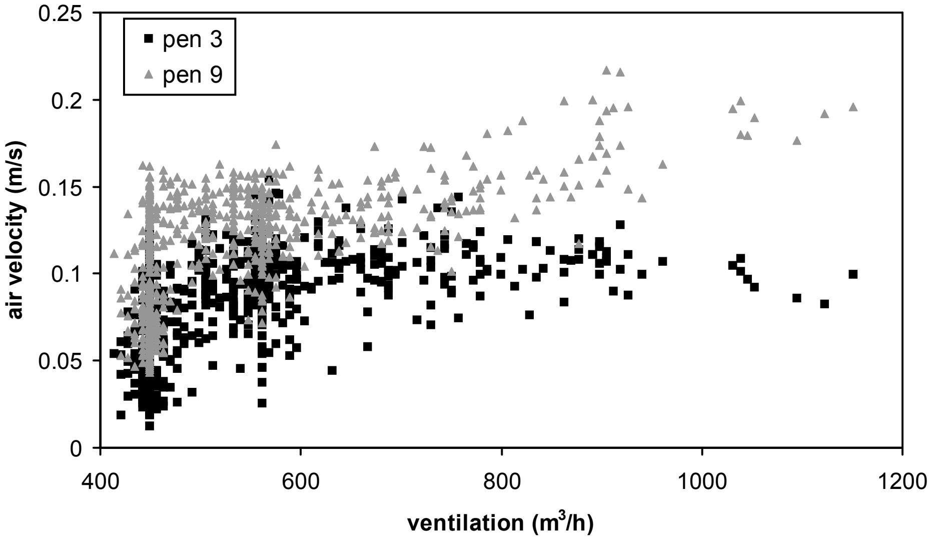

Figure 9. Effect of ventilation rate on air velocity at location 2-2-2 in pen 3 and pen 9 during one batch (except for first week) of weaned piglets in experimental room (hourly averages).

The distribution of the air velocities during the batch is shown in figure 10. There was a clear and significant difference in average air velocity between pens 3 and 9 ($P < 0.001$). The average difference was 0.04 m/s. The recommended maximum value for air velocity in the AOZ for weaned piglets is 0.15 m/s (Van 't Klooster et al., 1989). The air velocity in pen 9 was higher 21% of the time, in pen 3 it was higher about 2% of the time.

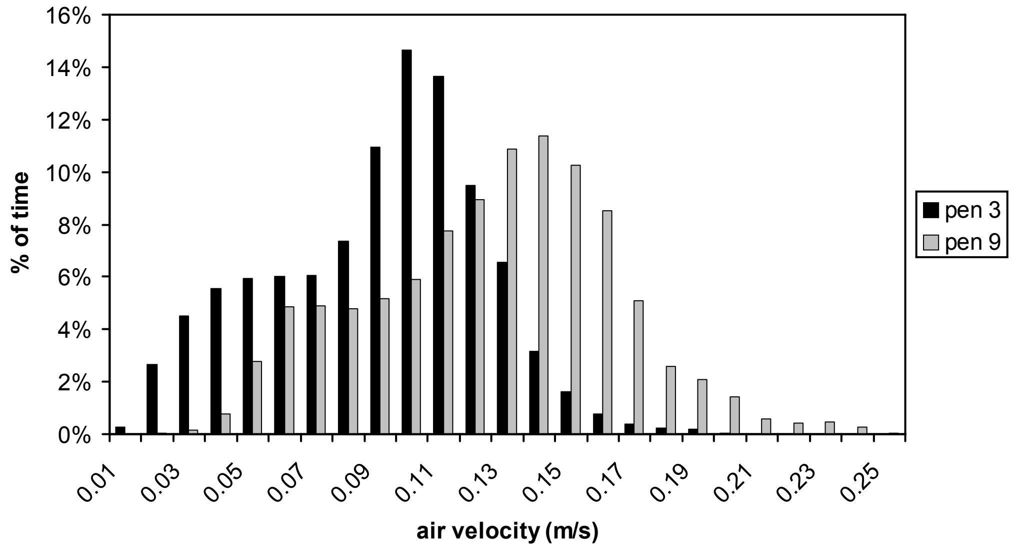

Figure 10. Distribution of air velocity measurements (300-s averages) at location 2-2-2 in pens 3 and 9 during one batch (except for first week) of weaned piglets in experimental room.

Besides differences in air velocity, there will be more climatic differences between pens 3 and 9 that might result in differences in animal production, animal health, and animal welfare. The fresh air supply in pen 9 was better than pen 3. Only the combination of air quality aspects, air velocity, and air temperature gives information about the quality of the climate in the AOZ, and thereby on the performance of the ventilation system. The measuring system described in this article can be combined with those for air quality and temperature in the AOZ as described in earlier work (Van Wagenberg and Smolders, 2002). This system can be used to determine the performance of ventilation systems and to compare ventilation systems.

Conclusion

Air velocity in the AOZ of occupied pig rooms can be measured using ultrasonic anemometers. A wire protection cage is necessary, but does affect the air velocities measured. To determine the time averaged air velocities a standardized calculation method, sample frequency, and aggregation interval can be used. A 1-Hz sample frequency and a 300-s aggregation interval is proposed for rooms for weaned piglets. Within the AOZ there will be differences in air velocity, and therefore the measurement location needs to be determined in a preliminary study to find a representative location for the occurring air velocity in the resting area of the pigs. Animal resting locations were essentially unaltered by the presence of a static anemometer, and animal activity had little impact on the air velocity measured. In a door-ventilated room the air velocity in pens at the back of the room was 0.04 m/s higher than in a pen closer to the door, resulting in differences in microclimate between the different pens within one room.

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CHAPTER 4

Methods for Evaluation of Thermal Environment in the Animal Occupied Zone for Weaned Piglets

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Abstract

Two evaluation methods are introduced for expression of the quality of the thermal conditions in the Animal Occupied Zone (AOZ) in rooms for weaned piglets. One method uses only the AOZ temperature, while the other uses the kata-value (KV), which combines air velocity and temperature and indicates the heat loss to the environment. AOZ thermal conditions should be within the Thermo Neutral Zone (TNZ) of the piglets. The methods use two new numerical indicators, based on the duration and the magnitude of excess of AOZ thermal conditions outside the TNZ, one referring to the number of degree-hours (°Ch) and the other to the number of kata-value-hours (KVh) during a batch. The objective was to evaluate the two methods in a door-ventilated room for weaned piglets.

In the experiment, temperature was measured in all 10 pens of a room and air velocity in 3 pens, during 8 successive batches together lasting about one year. Pens closer to the air inlet had higher temperatures and lower KV than pens in the back of the room. Momentary temperature difference between pens reached up to 7°C. During the first days of most batches, pen conditions in the back of the room were “too cold”; at the end of most batches pen conditions in the middle of the room were ”too warm”. The value of the two indicators varied per pen and per batch from 0 to 319 °Ch/ 0 to 219 KVh “too cold” and from 0 to 602 °Ch/ 0 to 793 KVh “too warm”. For “too warm” conditions there was a significant ($P<0.001$) and strong correlation between the two indicators (R^2 was > 0.96), for “too cold” conditions not (R^2 was > 0.48). Therefore, measuring air velocity in addition to temperature in the AOZ for recognition of “too cold” conditions had surplus value. Excluding outliers from one extreme warm batch, the maximum value of the indicator for “too warm” was 65°Ch. This indicator significantly affected feed conversion ratio, that increased with 0.0024 kg/kg per °Ch and daily growth and daily feed intake, that decreased with 0.0022 kg/animal and 0.0030 kg/animal respectively per °Ch.

The methods presented are useful tools in the technical evaluation of climate-systems and for a more optimal climate control in the AOZ.

Keywords. Kata-value, temperature, weaned piglet, Animal Occupied Zone, door-ventilated pig room, Thermo Neutral Zone

Introduction

The climatic environment of animals is an important aspect in livestock production, especially for weaned piglets. Directly after weaning piglets are subjected to many stresses, including being separated from the sow, being moved to a new and different environment, and changing from milk to a solid diet (Le Dividich and Herpin, 1994; McCracken et al., 1995). A widely accepted range for the optimal thermal conditions of the piglet is defined as the Thermo Neutral Zone (TNZ), which is the range of thermal environments with minimal metabolic rate (Van 't Klooster et al., 1989; CIGR, 1999; Quiniou et al., 2000; Van Ouwerkerk, 2000; CIGR, 2002). The limits of the TNZ are mostly expressed in air temperature, but air velocity is considered as an important factor too, as it is a component of the convective heat loss and thus the thermal comfort (Le Dividich and Herpin, 1994; Tao and Xin, 2003). This heat loss is indicated in the kata-value (*KV*), that combines air temperature and air velocity, and was previously used in pig rooms by Scheepens et al (1991) and Lambers and Van der Wolf (1996). Models have been developed that calculate the theoretical limits of the TNZ (Bruce and Clark, 1979; Van Ouwerkerk, 2000), either expressed in air temperature or in *KV*. When the thermal environment of the piglet exceeds the limits of the TNZ, animal performance (feed intake, growth, feed conversion ratio) is expected to deteriorate (Van 't Klooster et al., 1989; Quiniou et al., 2000; Van Ouwerkerk, 2000) with under certain circumstances an increased risk for animal health. This has been confirmed in studies where pigs are put in experimental climate chambers and are exposed to an adverse thermal environment outside the TNZ, such as high temperatures and low air temperature in combination with a high air velocity (Verhagen et al., 1987; Scheepens et al., 1991; Herpin and Lefaucheur, 1992; Nienaber et al., 1996; Collin et al., 2002).

The problem is that there is no established method to indicate the quality of the thermal environment of a piglet during a batch (i.e. one group of piglets managed all-in/all-out in a specific room) regarding the time course of temperature and/or *KV*. Batch average values of temperature or *KV* are not suitable because in the averages too cold moments compensate for too warm moments. Furthermore, the climatic demands of the piglets (the limits of the TNZ) change in time during the batch, for example the desired temperature in the beginning of a batch is too warm for later in the batch. Then, a complication is that *KV* gives a better insight into the thermal environment than air temperature alone, but measuring air velocity requires

expensive and vulnerable equipment (Van Wagenberg and de Leeuw, 2003). Therefore, this need for measuring air velocity in addition to air temperature should be argued.
Another aspect of climate optimization in pig rooms is the spatial gradients of climate factors. Pig rooms are commonly equipped with heating and ventilation systems to maintain the right indoor air quality and thermal environment. These systems are generally controlled based on room climate, using one or more temperature sensors somewhere in the room. But, within a ventilated pig room thermal environment (air temperature, air velocity) will depend on the location within the room (Randall, 1980; Van ‘t Klooster, 1994; Hoff, 1995; Van Wagenberg and Smolders, 2002; Van Wagenberg et al., 2005). An obvious example is a door-ventilated room where fresh air enters the room through the door opening with a maximum air velocity of circa 1 m/s. Via the operator walkway the air flows over the solid pen partitions into the pens. In this common Dutch system it is known that air distribution over the pens is not homogeneous resulting in differences in thermal environment between pens (Van Wagenberg and Smolders, 2002; Van Wagenberg and de Leeuw, 2003; Van Wagenberg et al., 2004). When evaluating heating and ventilation systems the thermal conditions in the region around the pigs, called the Animal Occupied Zone (AOZ), are of most concern (Heber et al., 2001; Zhang et al., 2001). This heterogeneity in the room and heterogeneity within the AOZ should be taken into account for providing optimal climatic conditions to the animals.

In this study two evaluation methods are introduced that express the quality of the thermal environment of weaned piglets in the AOZ by numerical indicators, using existing knowledge about the limits of the TNZ of the piglets. The first method takes into account the temperature; the second is based on *KV* in the AOZ. The number of hours that the AOZ thermal conditions exceed the limits of the TNZ, as well as the magnitude of the excess is calculated. The objective of this study was to apply the two methods in a door-ventilated room and to compare their potential value for AOZ climate evaluation and control for weaned piglets. Thereby, the relationship between both indicators is investigated as well as the effect on the piglet performance when the climate exceeded the limits of the calculated TNZ.

Material and methods

Kata-value

The kata-value (*KV*) indicates the heat loss of warm (skin) surfaces like those of pigs. The relation between *KV*, air temperature *T* (°C) and air velocity *U* (m/s) was empirically determined by calculating the heat loss from the measured time span for cooling a silver coated glass bulb filled with alcohol from 38° to 35°C. It yielded (Crauwels et al., 1991):

$$KV = (36.5^{o}C - T)\cdot(1.07 + 1.73\sqrt{U}) \qquad \textbf{(1)}$$

where *KV* is expressed mW/cm^2. *KV* increases when the conditions get colder. Physical analysis of the heat transfer coefficient in this formula (*1.07 + 1.73√U*) learns that the first term (*1.07*) indicates heat transfer independent of air velocity (radiation, natural convection) and the other term indicates forced convection. For laminar flow the heat transfer coefficient is, as generally found in literature, proportional to √*U* (~ √*Reynolds*) (Kreith, 1976). Figure 1 shows *KV* for various temperature – air velocity combinations.

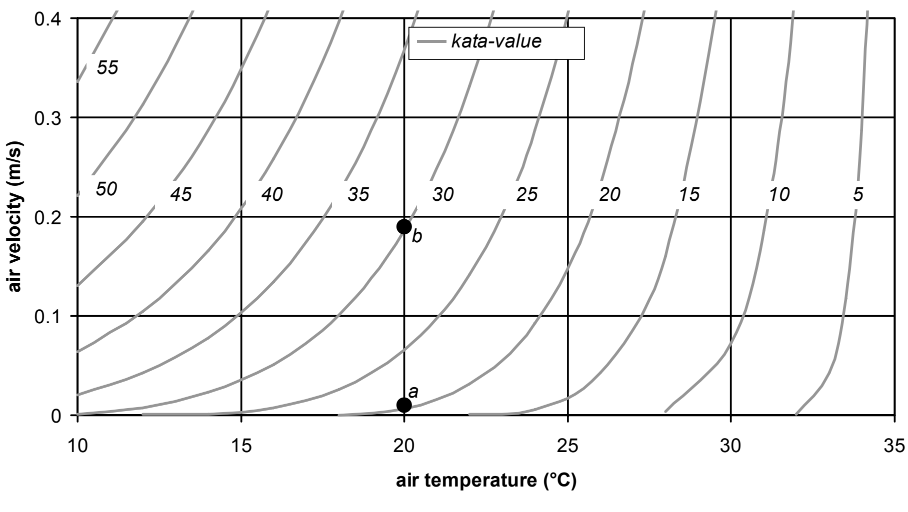


Figure 1. Range of kata-values calculated for various temperature - air velocity combinations (*a* en *b* are reference points in the text)

At air temperature of 20°C, and air velocity of 0.01 m/s (point *a* in figure 1), *KV* is 20.5. When the air velocity is 0.19 m/s at the same air temperature, *KV* is 30.1 (point *b* in figure 1), indicating a 50% higher sensible heat-loss. Because the contact surface between a weaned piglet and the air varies from 1000 cm^2 to 3000 cm^2 as the piglet grows from 8 up to 23 kg (Van Ouwerkerk, 2000), *KV* of 30 reflects sensible heat losses between 30 to 90 W per piglet.

Thermo Neutral Zone of weaned piglets

For calculation of the TNZ limits for both temperature and *KV*, the simulation software ANIPRO (Van Ouwerkerk, 2000) was used. ANIPRO is based on earlier detailed studies on thermal comfort of pigs (Bruce and Clark, 1979; Sterrenburg and Van Ouwerkerk, 1986a and b). The conditions used as input for ANIPRO were based on the average situation in the experimental room; the piglets were weaned and moved directly to the experimental room, where they grew from 8 till 23 kg in circa 35 days; there was a solid insulated floor; floor heating was on during the first 8 days; surfaces for radiation heat losses (wall, roof, pen partitions) had the same temperature as the air; total feed intake increased almost linearly from 0.1 kg per day on day 0 to 1.1 kg per day on day 35, the energy content of the feed was conform the diet used in the experiment and is described in the next section. The limits calculated are given in figure 2; the temperature zones calculated are based on a constant air velocity of 0.10 m/s.

(a) (b)

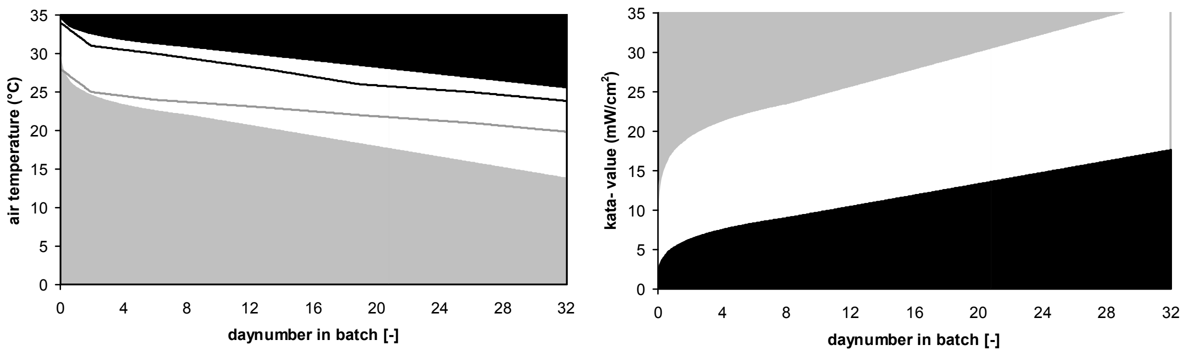


Figure 2. Thermo Neutral Zone (white area) expressed in temperature (a) and the kata-value (b) for weaned piglets (grey area = “too cold”, black area = “too warm”) and including the climatic settings (grey line is set point for room heating and black line indicates the temperature with maximum ventilation in the room)

TNZ limits as shown in figure 2 (a) and (b) were used in the evaluation methods, thereby ignoring differences in TNZ limits between pens due to possible differences in animal performance between pens. The course of AOZ thermal conditions was compared with the

TNZ limits, and the cumulative excess was determined using the duration and the magnitude of the excess of these limits, and is expressed in the number of *degree-hours* (*°Ch*, method 1) or *kata-value-hours* (*KVh*, method 2) outside the TNZ per batch. An excess of the TNZ limits during 2 hours by 1°C, but also exceeding this limit by 2°C during 1 hour, resulted in a cumulative excess of 2*°Ch* and so on. The degree-hours method was used before in model simulations to quantify heating or cooling requirements in finishing pig rooms, but spatial gradients and the relation with TNZ limits were ignored (Panagakis and Axaopoulos, 2004). Periods with an excess of the lower limit of the TNZ expressed in temperature, and an excess of the upper limit of the TNZ expressed in *KV*, are defined as "too cold" in this paper. Periods with excess on the opposite side of the TNZ, are defined as "too warm".

Experiment

Housing system and animals

The experiment was carried out in a door-ventilated room for weaned piglets at the experimental pig farm of the Animal Sciences Group in Raalte, The Netherlands, in the period from 10 May 2002 to 12 June 2003. The room was operated according to the "all in-all out" principle. In total 720 piglets were used in the study, distributed over 8 batches. Male piglets were castrated. The piglets were weaned at 4 weeks and divided into groups of 9 piglets per pen. The piglets from the same sow were distributed over different pens as much as possible. The aim was to have 4 (or 5) barrows and 5 (or 4) gilts per pen with an average weight between 8 and 9 kg. Piglets weighing less than 5 kg or more than 11 kg were excluded. The piglets received feed and drink water ab libitum. Feed was provided by dry-feeders. The first two days after weaning they received creep feed (11.79 MJ NE). In the next three days they were gradually switched over to a pre starter diet (9.3 MJ NE, 10.1 g/kg lysine), which was fed until day 7 after weaning. Then, from day 8 until day 10 after weaning the piglets were gradually switched over to a starter diet (9.5 MJ NE, 10.1 g/kg lysine), which was fed until the end of the rearing period. Most batches ended after 32 days; exceptions included batch 4 with 28 days and batches 6 and 8 with 39 days.

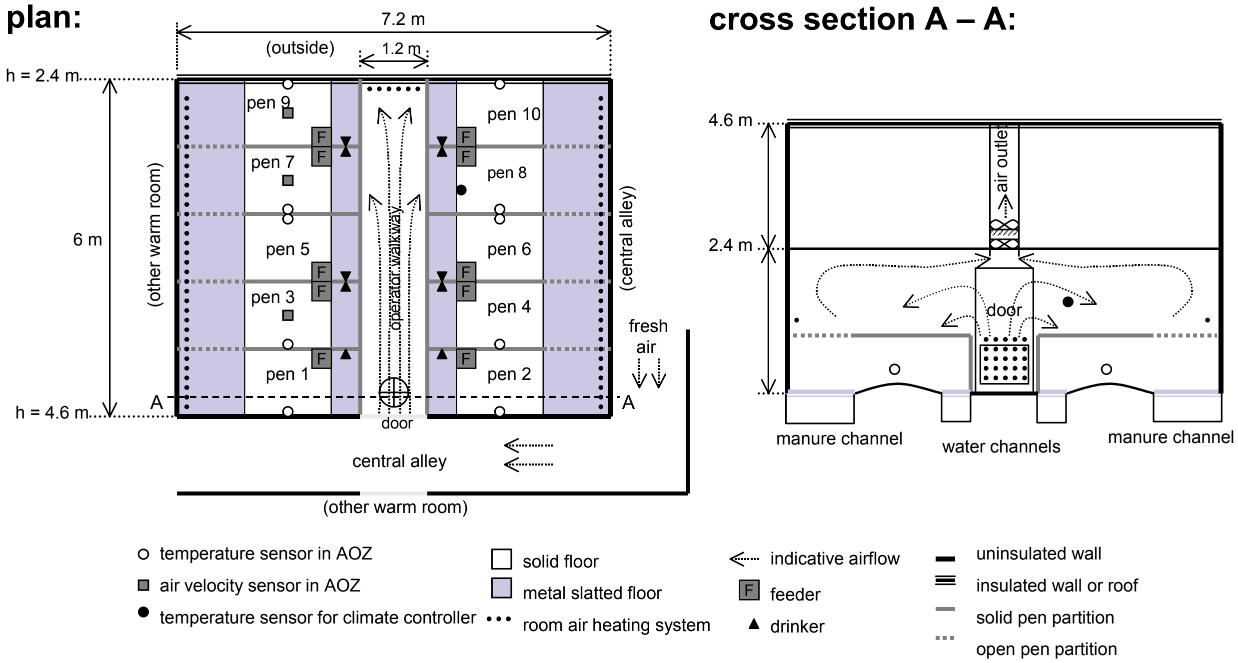


Figure 3. Plan and cross section of compartment with numbered pens (h = height in the room)

Description of the room

In figure 3 the plan and cross section of the experimental door-ventilated room are shown. The internal walls of the building were not insulated, and the central alley functioned as a common air inlet for the rooms on both sides. Fresh air was preheated in the central alley to a minimum of 5°C when outside temperature was lower. The right side of the experimental room bordered the relatively cold central alley; the left side bordered another warm room. In the experimental room were 10 pens each for 9 piglets, 5 pens on each side of the central operator walkway. As seen from the walkway, in the front of the pens was a metal slatted floor above the water channel (which is filled with a layer of water in the beginning of the batch and is designed to collect small amounts of manure and urine produced in the front of the pen), followed by a solid concrete floor with a spherical shape and with floor heating, and in the back of the pens was a metal slatted floor above the manure channel. No bedding material was used in the pens. Room air heating was available via (water filled) heating pipes on both sides of the room and a radiator in the back of the operator walkway. Ventilation air entered the room through an opening in the door and flowed over the operator walkway to the back of the room. Air was removed from the room by a ventilator in a circular ventilation shaft just behind the door at 2.1 m height. 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. A detailed description of the experimental room is given by Van Wagenberg and de Leeuw (2003) and Van Wagenberg et al. (2004).

Control of heating and ventilation was based on one room temperature measurement at 1.5 m height above pen 8 (fig. 3). Table 1 shows the climate computer settings used. The set point for room heating (second column in table 1) and the temperature where the maximum ventilation was reached (4°C above the stated set point for ventilation, fourth column in table 1) are also plotted in figure 2, to illustrate that climate settings were such that room air heating switched on before the lower limit of the TNZ was reached and that maximum ventilation capacity was used as soon as room temperature reached the upper limit of TNZ.

Table 1. Temperature set points in the experimental room for room heating, floor heating and ventilation, and the minimum and maximum ventilation.

Day No.	Temperature Set Point (°C)			Ventilation per Piglet (m^3/h) [a]	
	Room Heating	Floor Heating	Ventilation [a]	Minimum	Maximum
2	28	40	30	4	10
4	25	40	27	4	11
8	24	35	26	5	13
21	18	25	21	5	20
28	18	25	21	6	25
49	17	20	20	6	25

[a] Set point indicates lower end of p-band (temperature range between minimum and maximum ventilation), p-band was 4°C

Measurements and recordings

In all pens air temperature in the AOZ was measured at one point at circa 0.15 m height, 1 m from the front pen partition (halfway the solid floor) and circa 0.05 m from the side pen partition at the opposite side of the feeder by using Pt100 sensors (accuracy 0.1°C). To protect the sensors from manipulation by the piglets they were placed in cages (depth 0.09 m, width 0.14 m and height 0.22 m) made of 6 mm diameter iron wire and with a mesh width of 25 mm by 25 mm. Momentary temperature values were logged with an interval of 600 s. Air velocity was measured in pens 3, 7 and 9. These pens were chosen because they were on one side of the operator walkway and distributed over the depth of the room to give insight in the

differences in AOZ climate between pens. Ultrasonic anemometers (Gill, Windmaster 1086M) were used at 0.3 m height, 1 m from the front pen partition and 0.6 m from the side pen partition. Based on earlier research (Van Wagenberg and de Leeuw, 2003), the measuring frequency was set at 1 Hz, and logging interval was 300s. The accuracy was 0.01 m/s. The measuring system used is described in detail by Van Wagenberg and de Leeuw (2003). Temperature of the inlet air (at 0.2 m height in the door opening) was measured (Pt100 sensor, accuracy 0.1°C) and recorded every 600 s.
Animal performance was measured by weighing each piglet on day 0, on day 18 and at the end of the batch. On day 18 and at the end of the batch the total feed supply per pen over the preceding period was registered. The data were used to calculate the average daily growth per piglet (individual) and per pen (pen average), the pen average daily feed intake per piglet and the pen average feed conversion ratio. In case of culling, the bodyweight of the culled piglet was measured, to estimate the amount of feed that was consumed by this individual piglet. These piglets were not used for calculating average animal performance (in total 29 piglets were culled).

Data analysis

Kata-value was calculated based on hourly average values of the temperature and air velocity. The course of the temperature in all 10 pens, and the course of *KV* in 3 pens were analyzed and compared with the calculated limits of the TNZ. The cumulative excess of the TNZ limits in °*Ch* and *KVh* was determined per pen and per batch separated for days 0 - 18 and for days 18 to end of batch. The cumulative excesses in °*Ch* and in *KVh* were compared with a linear regression analysis (Genstat, 1993) in order to derive the surplus value of measuring air velocity.
With the ANOVA procedure in Genstat (1993) it was tested if there were significant differences in animal performance between pens. The effect of cumulative excess in °*Ch* and in *KVh* on animal performance was examined separately for days 0 to 18 and for days 18 to end using the statistical model (Genstat, 1993):

$$Y = constant + starting\_weight + X + e \qquad \textbf{(2)}$$

where *Y* is the pen-average daily feed intake per piglet, the pen-average feed conversion ratio, the pen-average daily growth per piglet, and where *X* is the cumulative excess of TNZ limits (in both *°Ch* and *KVh*) and *e* is the error term. The *starting_weight* was the average bodyweight per pen on day 0 or on day 18. The same model was also used to analyze the individual growth per piglet per day (*Y*), in that case the *starting_weight* was the individual weight per piglet.

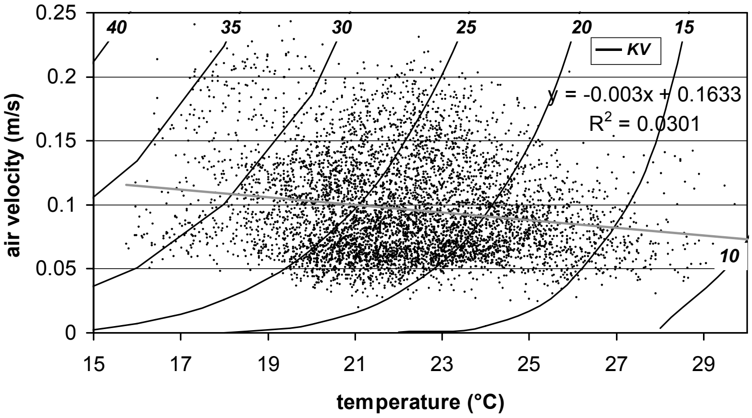
In the analysis of pen average piglet performance, data records were ignored when the pen-average bodyweight was less than 18 kg at the end of the batch. In the analysis of individual piglet data, data records were ignored if piglet weight at the end of the batch was below 16 kg. Reason for this is that the calculated TNZ limits wouldn't be representative for these slow growing animals, and therefore the calculated cumulative excess would not be representative. In analysis of pen averages, data were also ignored when in a pen during one batch two or more animals were culled; it would diminish reliability of the pen data. Furthermore, when the cumulative excess of TNZ limits during one batch was extremely high compared to the other experimental batches, those data were ignored to eliminate the disturbing effect of these outliers in the Genstat analysis. The applied statistical model will not be useable for accidental extreme cold or warm batches.

Results

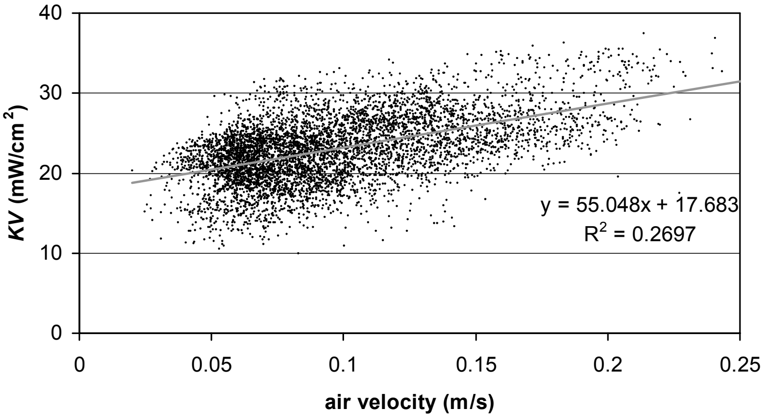
Temperature and air velocity measurements and calculated kata-value

In figure 4 the hour-average temperatures and air velocities as measured in pen 9 during all 8 batches (more than 7 000 hourly averages) are plotted versus each other and versus *KV*.

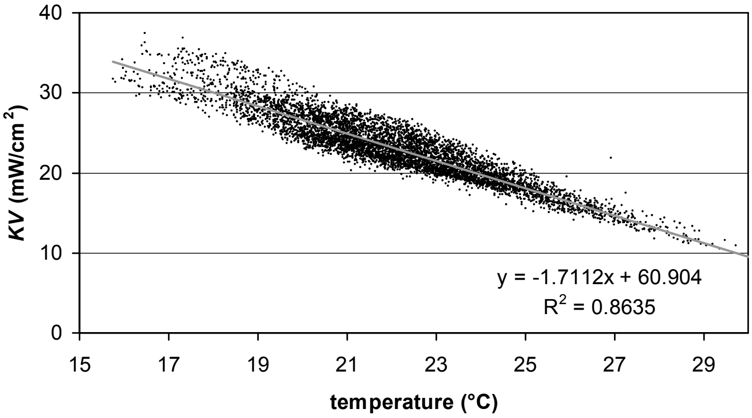
The distribution of the data points as measured in pen 9 was also representative for pens 3 and pen 7 (not shown). The only difference was that in pen 9 the conditions were often colder, the temperatures measured lower and air velocities higher, resulting in higher *KV*.



(a)



(b)



(c)

Figure 4. Relationship between hourly average temperatures, air velocities and kata-values for pen 9 during the 8 experimental batches (grey lines are trendlines)

Figure 4(a) shows that air velocity varied from 0.03 m/s to 0.25 m/s, almost independently of the temperature (R^2=0.030). Only at temperatures above 25°C, the air velocity hardly reached above 0.15 m/s. At all air velocities there was much variation in *KV*, and, as expected, *KV* was on average somewhat higher at higher air velocities (figure 4(b)). Comparison of figures 4(b) and 4(c) shows that the relationship of *KV* with temperature (R^2=0.86) is stronger than with air velocity (R^2=0.27). At lower temperatures there was some variation in *KV*, while at higher temperatures the variation in *KV* became smaller and temperature appeared to be a good predictor for *KV*. Figure 4 indicates that air temperature was the most determinant factor for *KV* under the experimental conditions.

In almost all pens and during all batches, “too cold” moments only occurred during the first 18 days of the batch, and “too warm” moments only after day 18 (data are not shown). Figure 5 shows examples of the course of the temperature and *KV* for two pens during a summer and a winter batch. The dotted vertical lines indicate day 18 when the piglets were weighed.

Despite the change in climate computer settings during a batch of 10°C to 11°C (table 1), AOZ temperatures during a batch didn’t change in this same amount (figure 5). This is partly due to the increased heat production of the piglets and partly to the limited possibilities to remove the heat from the room with ventilation air. During both batches in pen 3, temperature was higher and *KV* was lower than in pen 9. The frequent fluctuations in the curves show the day-night pattern of AOZ temperature and *KV*. In the beginning of the winter batch, the AOZ in pen 9 was “too cold”. At the end of both batches, pen 3 got “too warm”. During the winter batch the temperature difference between pen 3 and pen 9 reached up to 7°C. This could result from the non-homogeneous air distribution due to an increased ventilation rate at the end of the batch.

Cumulative excess of TNZ limits

The cumulative excess of the TNZ limits in both *°Ch* and *KVh* for pens 3, 7 and 9 is shown in figure 6. Negative values indicate “too cold” conditions, and are for days 0 to 18; positive values indicate “too warm” conditions and refer to days 18 to end of batch.

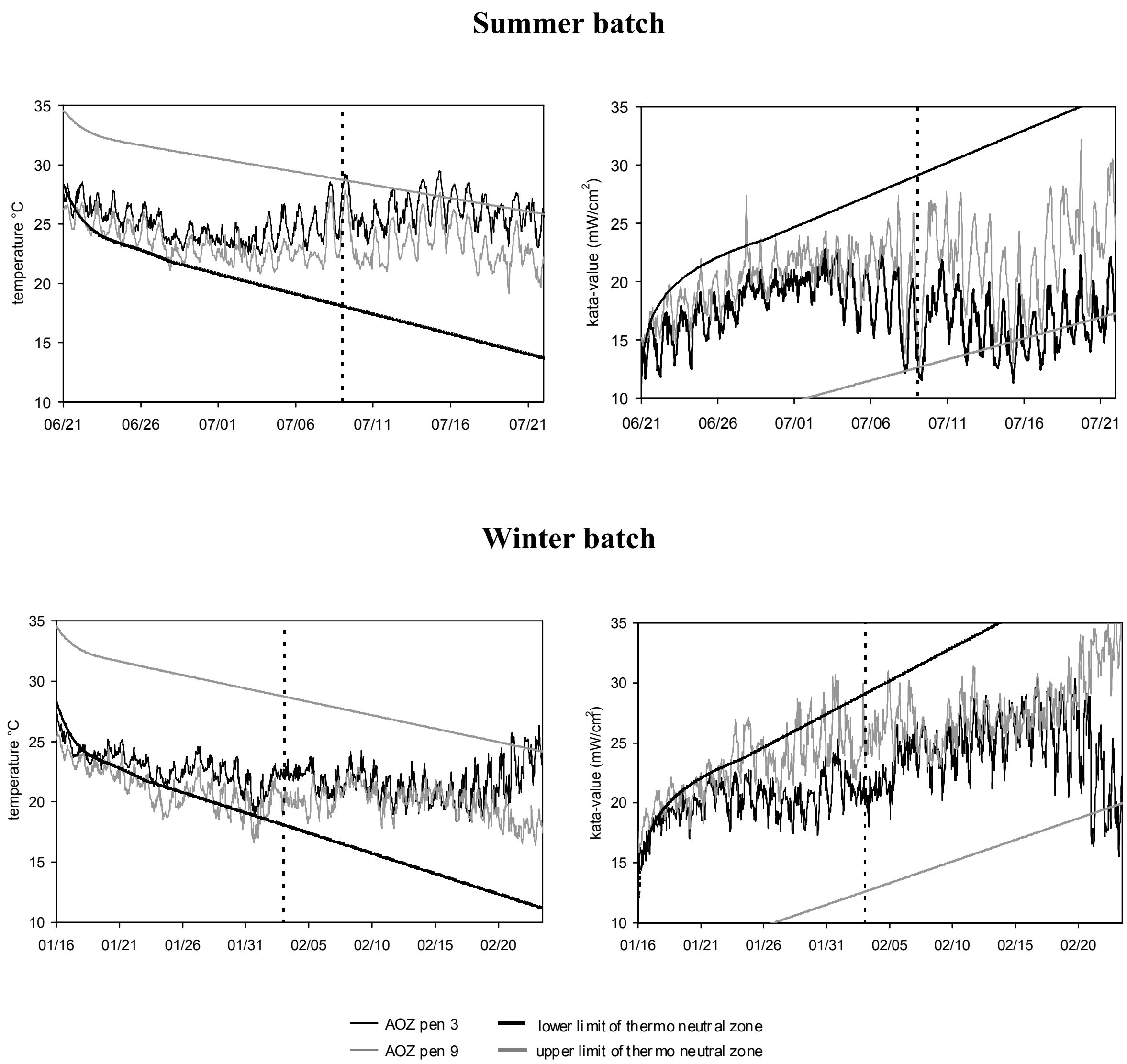


Figure 5. The course of hourly averages of the temperature and the *KV* in pens 3 and 9 during a summer batch (batch 2) and a winter batch (batch 6) and the limits of the Thermo Neutral Zone.

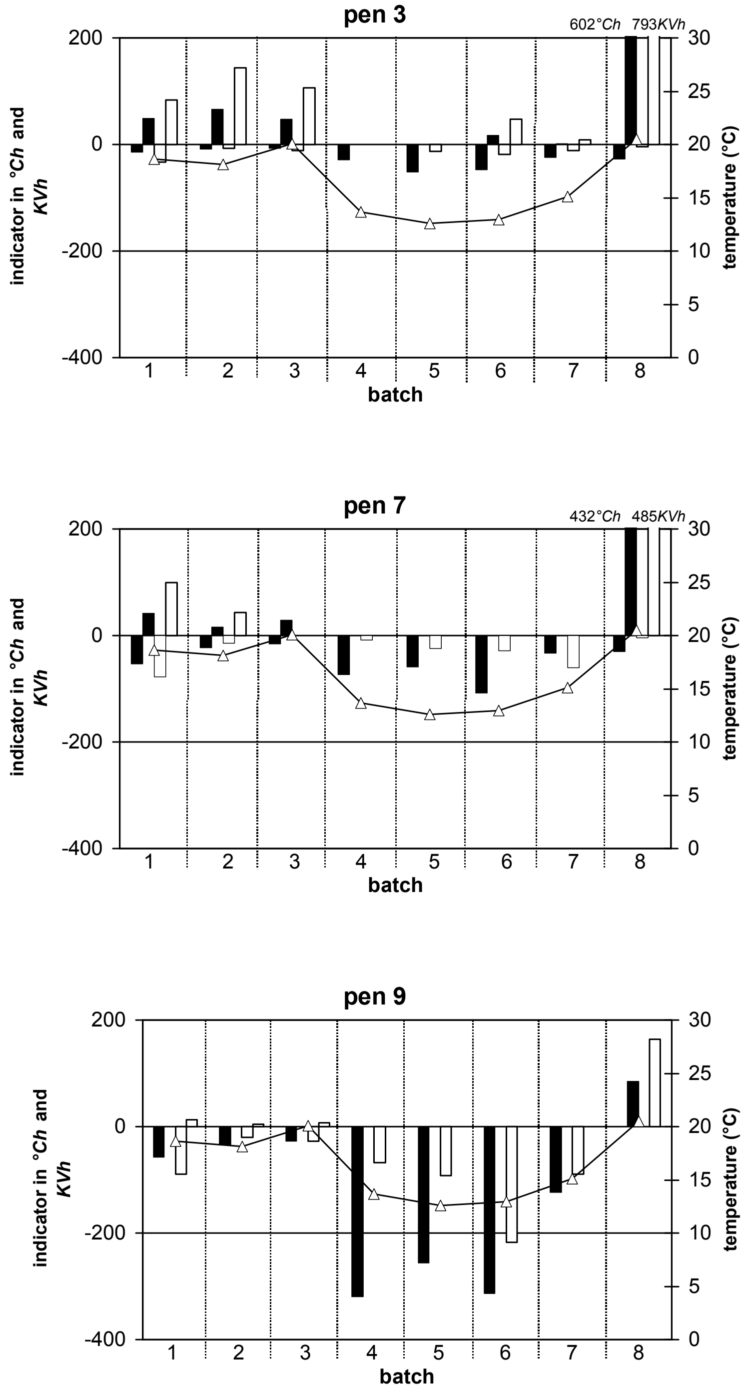
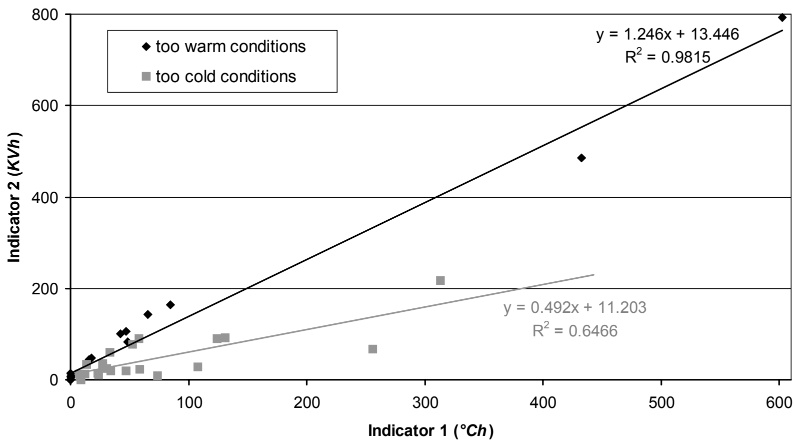


Figure 6. Cumulative excess of Thermo Neutral Zone limits (black bars: *°Ch*, white bars: *KVh*) in pens 3, 7 and 9 ("too warm": positive values, for days 18 to end of batch; "too cold": negative values, for days 0 to 18) and the average air temperature in the inlet (line with Δ) during the 8 experimental batches

There were large differences in cumulative excess of the TNZ limits between pens and between batches. Batches in the winter period (batches 4, 5 and 6) were much colder than the other batches and pen 9 was colder than pen 3 and 7. In batch 4 the highest cumulative excess "too cold" in *°Ch* (319) was recorded in pen 9, in batch 6 the highest cumulative excess "too cold" in *KVh* (217) was recorded. From the remaining batches especially batch 8 was extremely warm, in pen 3 602*°Ch* and 793 *KVh* were recorded.
For comparing the values of both indicators per pen per batch, they were plotted against each other. It was done for the real value and the logarithm. The logarithmic plot was made to reduce the influence of some extreme high values of the indicators on the correlation (batch 8), excluding data points where one of the indicators (or both) had the value "0".



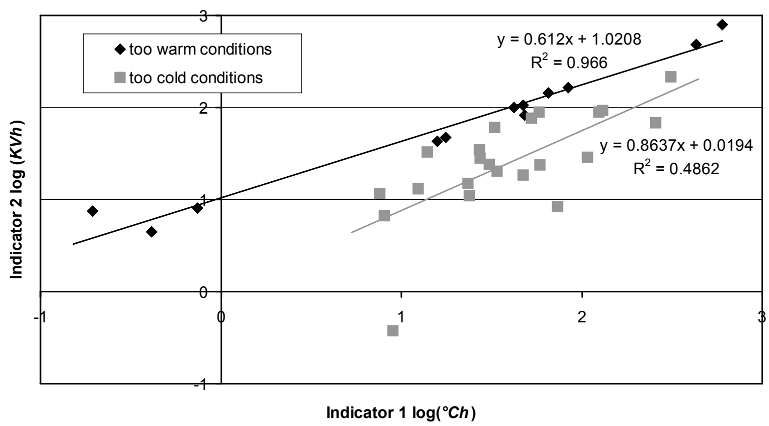


Figure 7. Relation between the cumulative excess of TNZ limits expressed in *°Ch* and *KVh* (on natural scale and logarithmic scale) in pens 3, 7 and 9 over the 8 experimental batches.

The result of the linear regression analysis showed that all relations were significant ($P<0.001$). Figure 7 shows that the values of both indicators for “too warm” conditions are strongly correlated ($R^2>0.96$). For “too cold” conditions, the correlation is less ($R^2>0.48$). This confirms the observation in figure 4(c) where *KV* varied more at relatively low temperatures.

Cumulative excess per pen and animal performance

The pen average cumulative excess of temperature and *KV* outside the TNZ, after data selection according to the criteria given in Material and Methods section, is shown table 2. Data of day 18 to end of batch 8 were ignored because of extreme warm AOZ conditions. After this selection the maximum cumulative excess “too warm” was 65*°Ch* and 143 *KVh* (both recorded in pen 3 during batch 2).
Table 2 shows that pens 2 and 10 have on average the highest cumulative excess for indicating “too cold” conditions. Both pens are on the right side of the operator walkway in the room. Behind the non-insulated wall on this side of the room was the relatively cold central alley. The average cumulative excess for indicating “too warm” conditions was generally lower than for “too cold” conditions, and was highest in pen 3. Except for pens 1 and 2 in the front of the room that bordered the colder central alley with a non-insulated wall (figure 3), pens generally got colder towards the back of the room (from pens 3 to 9, or from pens 4 to 10).

Table 2 also shows pen average piglets performance after applying the selection criteria. These criteria resulted in ignoring 7 batch average animal performance values because 2 or more piglets were culled in one pen during one batch, and 6 batch average values were ignored because the average piglet weight at the end of the batch was lower than 18 kg. There were clear and significant differences in growth from day 0 to 18, feed conversion ratio for days 0 to 18 and feed intake between pens. Pen 6 had the worst results from days 0 to 18, pens 4 and 7 the best. For days 18 to end the differences between pens were less.

In table 3 the results of the statistical analysis (equation 2) of the data on animal performance are presented. “Too cold” periods didn’t significantly affect the animal performance. “Too warm” periods (expressed in *°Ch*) significantly affected the feed conversion, daily growth (both pen average and individual), and daily feed intake. For example, the factors indicate that

50°*Ch* "too warm" in one pen after day 18 of one batch, results for in a higher feed conversion of 0.12 kg feed /kg growth (=50°*Ch**0.0024), a reduced daily growth of 0.11 kg/animal (=50°*Ch**0.0022) and a reduced daily feed intake of 0.15 kg/animal (50°*Ch**0.0030) in this period. The percentage of variance accounted for by the analysis is a summary of how much of the variability of the data can be explained by a fitted regression model, and indicates that there were other factors than used in the analysis that affected animal performance. The effect of the cumulative excess expressed in *KVh* for "too warm" conditions showed less significant results, probably due to the limited number of available data.

Table 2. Pen average cumulative excess of TNZ limits for temperature and *KV* and pen average growth per piglet per day, feed conversion ratio and daily feed intake per piglet separated for the days 0 to 18 and days 18 to end of the batch [a].

Pen	Cumulative excess "too cold" Days 0 - 18		Cumulative excess "too warm" Days 18 – end		Growth per piglet (kg/day) Days 0 – 18	Growth per piglet (kg/day) Days 18 – end	Feed conversion ratio (kg / kg) Days 0 – 18	Feed conversion ratio (kg / kg) Days 18 - end	Feed intake per piglet (kg/day) Days 0 - 18	Feed intake per piglet (kg/day) Days 18 – end
	°*Ch*	*KVh*	°*Ch*	*KVh*						
1	106	-	7	-	$0.235^{a,b}$	0.536^{a}	$1.69^{a,b}$	1.74	$0.392^{a,b,c}$	$0.930^{a,b}$
2	178	-	8	-	$0.236^{a,b}$	0.522^{a}	$1.78^{b,c}$	1.71	$0.420^{b,c}$	$0.892^{a,b}$
3	19	16	26	65	$0.233^{a,b}$	0.514^{a}	$1.70^{a,b}$	1.74	$0.386^{a,b}$	$0.885^{a,b}$
4	50	-	15	-	0.252^{b}	0.571^{a}	$1.61^{a,b}$	1.75	$0.406^{b,c}$	0.998^{b}
5	40	-	12	-	0.252^{b}	0.514^{a}	$1.73^{a,b,c}$	1.78	0.430^{c}	$0.911^{a,b}$
6	100	-	10	-	0.206^{a}	0.530^{a}	1.90^{c}	1.73	$0.399^{b,c}$	$0.912^{a,b}$
7	55	37	14	50	$0.230^{a,b}$	0.510^{a}	$1.60^{a,b}$	1.72	$0.356^{a,b}$	0.812^{a}
8	118	-	7	-	$0.230^{a,b}$	0.521^{a}	$1.72^{a,b}$	1.78	$0.387^{a,b}$	$0.906^{a,b}$
9	133	92	0	5	$0.245^{a,b}$	0.526^{a}	$1.64^{a,b}$	1.78	$0.399^{b,c}$	$0.933^{a,b}$
10	179	-	4	-	0.249^{b}	0.517^{a}	$1.65^{a,b}$	1.81	$0.408^{b,c}$	$0.942^{a,b}$

[a] different letters in the same column indicate significant differences ($P < 0.05$)

Table 3. Results of the statistical analysis of the data on animal performance.

Dependent Variable Y \ Explanatory Variable X		Cumulative Excess in °*Ch*						Cumulative Excess in *KVh*					
			% of var.	X		starting weight[c]			% of var.	X		starting weight[c]	
		N[a]	acc. for	P	factor[b]	P	factor	N[a]	acc. for	P	factor[b]	P	factor
Day 0 – 18 ("too cold")													
Pen Average	Feed Conversion	66	-	0.865	-	0.293	-	18	-	0.749	-	0.843	-
	Daily Growth	66	-	0.520	-	0.201	-	18	-	0.996	-	0.365	-
	Daily Feed Intake	66	-	0.167	-	0.758	-	18	-	0.499	-	0.589	-
Individual	Daily Growth	611	-	0.775	-	0.681	-	175	-	0.798	-	0.714	-
Day 18 – end ("too warm")													
Pen Average	Feed Conversion	58	12.2	0.013	0.0024	0.069	0.028	11	-	0.565	-	0.813	-
	Daily Growth	58	22.6	<0.001	-0.0022	0.024	0.010	11	-	0.411	-	0.367	-
	Daily Feed Intake	58	20.1	0.006	-0.0030	0.005	0.028	11	-	0.438	-	0.655	-
Individual	Daily Growth	545	12.6	<0.001	-0.0023	<0.001	0.019	158	15.6	0.021	-0.0006	<0.001	0.027

[a] The number of observations is in some cases different than the expected based on the number of experimental batches and pens. Besides the mentioned selection criteria, reasons for this are: (1) during batch 8 in pens 9 and 10 the temperature was not measured on from days 1 to 18, (2) during batch 3 the air velocity was not measured in pen 7.

[b] this factor indicates the effect of either an excess of 1°*Ch* or 1 *KVh* on the average animal performance variables for days 0 to 18 or for days 18 to end. By multiplying the factor with X the estimated effect can be calculated.

[c] for day 0 to 18 this is the starting weight, for day 18 to end this is the weight on day 18.

Discussion

In this study two evaluation methods are introduced that express the quality of the thermal environment in the AOZ of weaned piglets during a batch. The indicators were based on the cumulative excess of the TNZ limits by temperature expressed in *°Ch* or by kata-value (*KV*) expressed in *KVh*. Both indicators revealed good insight into the differences in AOZ climate between pens in a door-ventilated room. Colder pens in the back and next to non-insulated walls in the room and warmer pens in the middle could be distinguished. This confirms results of in earlier studies on the door-ventilation systems (Van Wagenberg and Smolders, 2002; Van Wagenberg and de Leeuw, 2003; Van Wagenberg et al., 2004) and confirms that focusing on AOZ climate control instead of room climate control in pig rooms is important. There was a significant ($P<0.001$) and strong ($R^2>0.96$) correlation between the two indicators for “too warm” conditions. Moments that where “too warm” regarding AOZ temperature, where also “too warm” regarding *KV* in the AOZ. This can be explained. At locations in the AOZ with a large amount of fresh air, temperature is expected to be relatively low and the air velocity relatively high. The air temperature distribution gives information on the fresh air distribution in a room with internal heat load (Boonen et al., 2002). However, for “too cold” conditions the indicators showed less correlation ($R^2>0.48$). It means that taking into account air velocity for recognition of “too cold” conditions can have surplus value. But even when air velocity is ignored in the change of focus from room climate to AOZ climate, important improvements in climate (control) systems can be achieved by reducing temperature differences between pens and better control of AOZ temperature.

The TNZ limits in evaluation method were based on the average animal performance in the room. This is disputable, because individual animals with a different than average performance will have other TNZ limits. We chose as a target that thermal conditions in all pens are optimal for piglets with average performance. Piglets have also mechanisms that influence TNZ limits, like adapting behavior or feed intake (Van Ouwerkerk, 2000; CIGR, 2002). For defining TNZ limits to be used in evaluating thermal environment it is hard to take into account those individual adaptations.

A relationship between the indicators for “too warm” conditions and animal performance was found. The significant relation found between the value of the indicators and the animal performance cannot simply be extrapolated to other batches in other situations. For example

for the 602°*Ch* “too warm” during batch 8 in this study, the effect per °*Ch* excess of TNZ limits will be different from the factors presented in table 3.
No relationship with animal performance was found for “too cold” conditions, while the values of the indicators for “too cold” conditions were higher than for “too warm” conditions. Assuming that the TNZ limits used are still valid for piglets nowadays, this is surprising. Constant too cold conditions are known to reduce feed conversion ratio (with about 0.044 $°C^{-1}$), and/or cause an increase in feed intake and/or result in a reduced growth rate (Le Dividich et al., 1992). A first explanation of the different outcome can be that the reported data are based on constant too cold conditions, while in our study too cold conditions mainly occurred during night periods while it was warmer during the day. Secondly, there was a possible difference between the values measured in the AOZ and the thermal conditions experienced by the piglets. In the experiment AOZ temperature was measured on opposite site of the feeder. Young piglets under cold conditions will prefer to lay behind the feeder, where the local microclimate is warmer (Van Wagenberg et al., 2005). Thirdly, in the data-analysis some data were neglected of culled and slow growing animals, where the reason for this could be that these animals were exposed to “too cold” conditions. Also in the data-analysis the batch effect was ignored, assuming that this normally reveals as an AOZ climate effect, while also other factors will play a role such as animal health situation and genetic features of the animals in a certain batch. Fourthly, the evaluation methods neglect some aspects in the interaction between thermal environment and piglets: (1) by not taking into account the fluctuations of the thermal environment (outside and within the AOZ), while it is known that quick changes in thermal environment under cold conditions are harmful (Scheepens et al., 1991); (2) under constant climatic stress pigs adapt to the conditions (Verhagen et al,, 1987; Le Dividich and Herpin, 1994); (3) there is diurnal variation in heat production of the piglets and thus in TNZ limits (Pedersen and Rom, 1998).

For a more detailed study on the response of piglets to a certain course of the climatic environment, comparative research in climate chambers could be done. Certain temperature or *KV* courses (based on encountered situations in the AOZ of practical buildings) could be used and animal performance data may be compared. This will help to quantify the importance of staying within the TNZ and to determine the costs of exceeding this zone due to less efficient production. This information can be used to judge and to optimize climate systems in pig houses, with the technical performance on the one hand and costs on the other.

Conclusion

- Two numerical indicators were introduced that reveal how much, during a batch of weaned piglets, the air temperature and kata-value (that combines air-velocity and air temperature) in the Animal Occupied Zone in the pen are outside the Thermo Neutral Zone of the animals. Both indicators allow sensitive discrimination in thermal conditions in a pig room both in space and time i.e. between the pens and between batches.
- In a door-ventilated room the value of the indicators varied largely between pens and batches, thereby clearly distinguishing colder pens in the back of the room and next to non-insulated walls, and warmer pens in the middle.
- For recognition of "too cold" conditions in the Animal Occupied Zone both air temperature and air velocity should be measured. For "too warm" conditions air temperature alone predicts the kata-value sufficiently.
- The cumulative excess in air temperature above the Thermo Neutral Zone, indicating "too warm" conditions significantly deteriorated animal performance.
- The study reveals that focusing on Animal Occupied Zone is necessary for creating optimal climate for weaned piglet. The methods presented can be used as a tool in the technical evaluation and comparison of climate-system designs.

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CHAPTER 5

Measurements and Simulation of Climatic Conditions in the Animal Occupied Zone in a Door-ventilated Room for Piglets

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Abstract

Climatic conditions in the animal occupied zone (AOZ) of a pig room are important for animal health, comfort and performance. Both practical measurements and numerical simulations could be used to assess the climatic conditions in the AOZ. The objective was to test the possibilities for using pig location patterns based on the real time monitoring as a thermal boundary condition in a numerical simulation model and to gain insight in the distribution of air velocity, air temperature and CO_2 concentration in the AOZ. Measurements were performed in a door-ventilated room for weaned piglets. Animal lying locations were recorded. The geometry of the air space including models for the pigs was constructed in AutoCad and imported in the numerical simulation program (Fluent 5). The measurements of three 1-hour periods were considered to be static situations, and are compared with numerical simulations.

Measured and simulated airflow direction in the AOZ did correspond, but in air velocity magnitude there were differences. The simulations agree with measurements in a preceding study, that show that the height above the solid floor is of crucial importance for the local air velocity. Both measurements and simulations showed a tendency for decreasing pen temperature when the distance to the door increased, but the measured temperatures were in general higher than the simulated. Adding radiation heat transfer in the simulations might decrease the difference. The differences between measured and simulated CO_2 concentration were relatively large, this could be caused by chosen simplifications in the simulations that influence the calculated airflow pattern and CO_2 distribution, such as not including the feeders in the model and assuming homogeneous conditions in the air inlet.

In the study it is proved to be possible to include boundary conditions obtained from conditions with live pigs, but some adaptations in the presented simulation model are necessary. Regarding the door-ventilation system, the study confirmed that the air distribution is inhomogeneous especially at high ventilation rates. The study confirms the expectation that numerical simulation has the potential to become an important tool for designing and improving ventilation systems for livestock rooms.

Keywords. Pig housing, air velocity, numerical simulation, air quality, air distribution, CFD.

Introduction

Air velocity, air temperature and contaminant concentration in the animal occupied zone (AOZ) of a pig room, are important for animal health, comfort and performance. The actual values depend on many factors, of which an important factor is the ventilation system design (Zhang et al. 2001; Van Wagenberg and Smolders, 2002). To assess the performance of ventilation systems, information on climatic conditions in the AOZ is needed.

Both practical measurements and numerical simulations could be used to gain insight in the climatic conditions in the AOZ. Measuring climatic conditions in the AOZ has been done in preceding studies than concentrated on air velocity in the AOZ and on fresh air supply to the AOZ based on gas concentrations (Van Wagenberg and de Leeuw, 2003; Van Wagenberg and Smolders, 2002). There are three disadvantages of practical measurements. A practical building is needed before the design of a ventilation system can be evaluated. Secondly it considers local measurements, which complicates the handling of heterogeneity within the AOZ. Finally, practical measurements demand expensive equipment and long-term experiments.

In a numerical simulation the room volume is divided into a cell structure (grid). Per cell a momentum, energy and a mass balance is expressed in differential equations. Between cells there is momentum, heat and mass transfer. Under given boundary conditions, this method can be used to simulate three-dimensional airflow, temperature and gas concentration distribution. For this, software packages are available. Numerical simulations have the potential to predict the climatic conditions in the AOZ. A number of numerical simulation studies have focused on the influence of room dimensions and inlet conditions in prediction of isothermal airflow in mechanical ventilated full scale livestock test rooms (e.g. Harral and Boon, 1997; Bjerg et al., 1999; Bjerg et al., 2002a; Bjerg et al., 2002b). Numerical simulation of buoyant airflow above a simulated pig is reported by Zhang et al (1999). Bjerg et al. (2000) investigated numerical simulation methods to predict airflow in a mechanical ventilated test room with and without thermal pig simulators and pen partitions. However, the complex environment of an actual occupied pig room, has not yet been reported. It is known that the presence of live pigs in a room has substantial effect on the characteristics of the airflow around them (Smith et al., 1999).

In this paper, practical measurements in a door-ventilated room for weaned piglets are described and compared with numerical simulation results. The objectives were to test the possibilities for using the boundary conditions obtained from conditions with live pigs in a numerical simulation model and to achieve the information on the distribution of air velocity, air temperature and CO_2 concentration in the AOZ. The level of agreement between measurements and simulation will illustrate the required further development of the numerical simulation technique. This paper thereby contributes to development of the simulation technique to an efficient tool in the design of practical ventilation systems.

Materials and methods

Experimental set-up

The experimental data were collected during three 1-hour periods during two subsequent days (2 hours during first day and 1 hour during second day). The periods were considered to be static situations: however, animals did move in the pens during the hour. Measurement results were compared with the numerical simulation. During the periods no persons entered the room, the feed system was inactive and the light was on for video recording of animal locations.

Description of room and animals

A door-ventilated room, in which fresh air enters the room through an opening in the lower part of the door, was used in this research (fig. 1). Next to the operator walkway are solid pen partitions (0.6 m height). Fresh air fills the operator walkway and flows slowly over the pen partitions into the pens. This ventilation system is commonly used in the Netherlands. The experimental room was located at the experimental farm in Raalte, The Netherlands. The room was built as a representative copy of the door-ventilation system most applied in practice for housing of piglets from 7 kg bodyweight to approximately 23 kg bodyweight. In figure 1 a plan and a cross section of the room is shown. In the room there were 5 pens on each side of the operator walkway, each for 9 animals. Each pen had 50% solid floor and 50% metal tribar slatted floor. The air inlet in the door was 0.58 m by 0.92 m (0.534 m^2). Initial measurements, with an ultrasonic anemometer located in the air inlet, have shown that airflow direction for all ventilation levels is perpendicular to the central alley. The exhaust air was removed from the room by a ventilator in a ventilation shaft, directly behind the door at 2.1 m height. For measuring and controlling the ventilation rate a measuring fan and an automatic valve were mounted in the ventilation shaft.

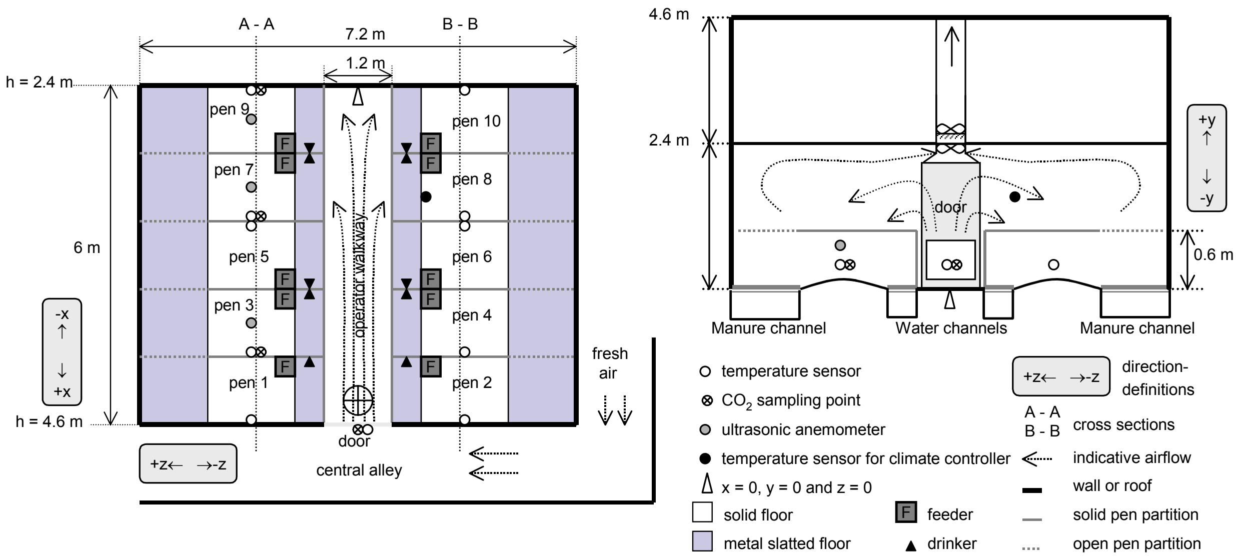

Figure 1. Plan and cross section of the compartment for weaned piglets, the measuring locations - the defined x, y and z axis are indicated.

A coordinate system was used in the room, figure 1. This coordinate system was based on the positioning of the ultrasonic anemometers and in such a way that the expected airflow directions in pens 3, 7 and 9 were positive.

Earlier work in the same room and in other door-ventilated rooms has shown that air distribution over the pens is not homogeneous (Van Wagenberg and Smolders, 2002 and Van Wagenberg and de Leeuw, 2003). At higher ventilation rates air is known to flow over the operator walkway to the back of the room before it flows over the pen partition. Much fresh air enters in the pens in the back of the room, resulting in effective removal of contaminants and heat from those pens, but increasing the risk for high air velocities in those pens. In the pens located near the front of the room there is less fresh air supply and air velocities are lower.

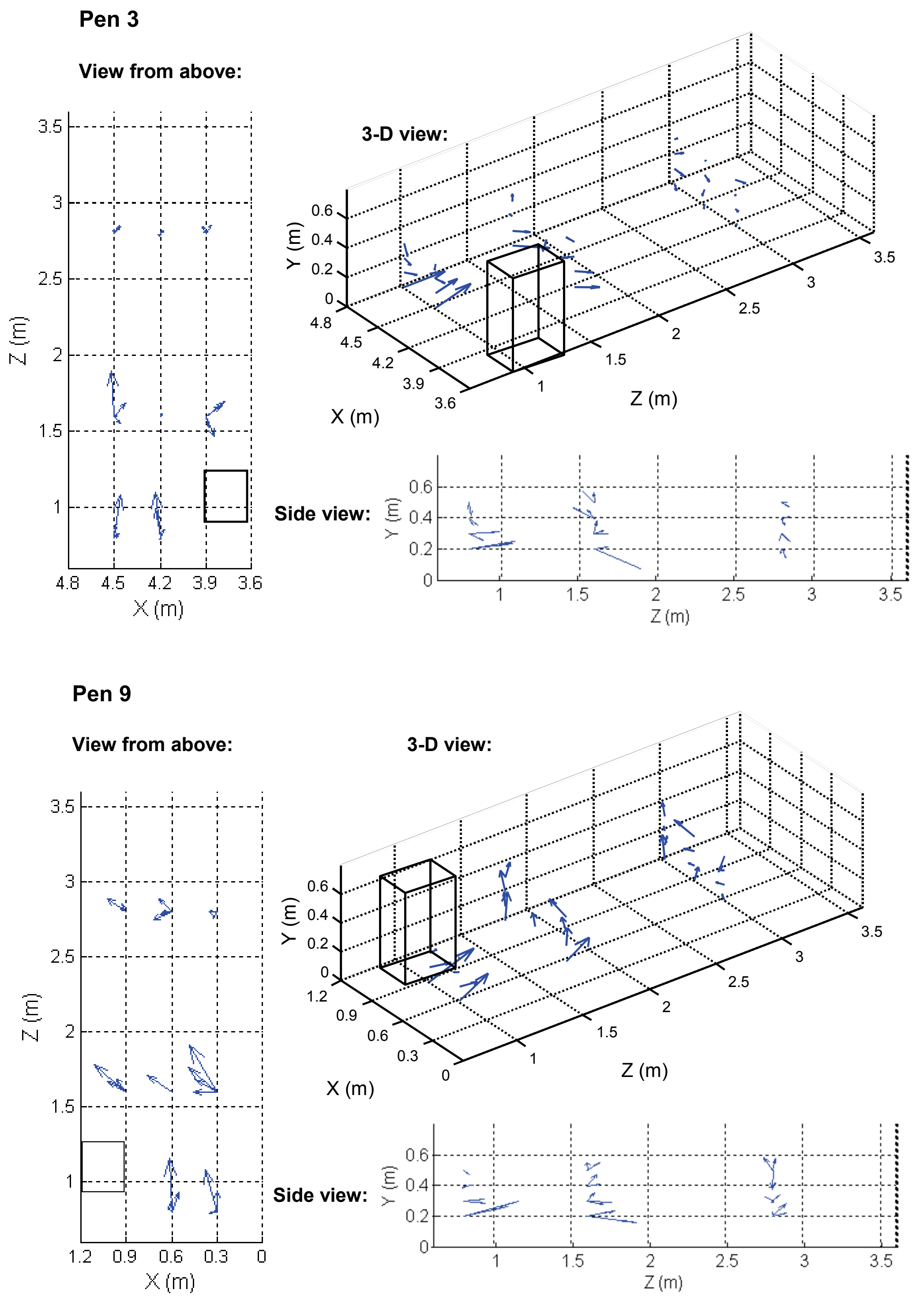

Figure 2. 3-D air velocity distribution in pens 3 and 9 in experimental room as measured in earlier research (numbers on axis in meters; x, y and z as in figure 1; arrow length of 0.5 m on axis ≈ 0.15 m/s; open box = feeder; average bodyweight piglets 8 kg; ventilation 340 – 490 m^3/h)

Three dimensional air velocity patterns in pen 3 and 9 of the experimental room were measured before. This was done by moving an ultrasonic anemometer over a grid within the AOZ. The method and the results are described by Van Wagenberg and de Leeuw (2003). The results of these measurements are plotted in graphs and are shown in figure 2

It was clear that air velocity and airflow direction in pens 3 and 9 depend on the location. In the front of both pens air velocity was higher than in the back. In the vertical velocity-profile above the solid floor (side view, Z= 1.6 m, measuring height Y varies from 0.2 to 0.5 m.), air velocity near the floor was highest and directed towards the back of the pen. In pen 3 the airflow direction changed direction at a height between 0.3 and 0.4 m and flowed to the front of the pen.

The measurements described in this paper were taken during days 18 and 19 in the production period. The average bodyweight of the piglets in the room was 13.1 kg. Feed intake was 650 gram/animal per day and the heat production was calculated at 55 W per animal, of which 38 W was sensible heat (Van Ouwerkerk, 2000). The ventilation was at minimal rate at a room temperature lower than 24.4° C, at higher temperature the ventilation increased automatically; the minimum and maximum ventilation levels were 5.0 and 18.0 m^3/h per piglet. The temperature range between minimum and maximum ventilation was 4° C and there was no additional heating.

Measurements and recordings

Air velocity measurements were performed with 3 ultrasonic Anemometers (Gill, Windmaster 1086M) protected by a cage and located in pens 3, 7 and 9, 1 m behind the front pen partition, 0.6 m from the side pen partition and 0.3 m above the solid floor. Time averaged air velocities were determined by averaging over 300 s with 1 Hz sample frequency. The accuracy was 0.01 m/s. A detailed description of the measuring system and strategy has been published before (Van Wagenberg and de Leeuw, 2003).
Air temperature measurements were performed with Pt100 sensors (accuracy < 0.1ºC). Sensors for pen temperatures were located in the middle of the solid floor in all pens, at 0.15 m height and at 0.05 m distance from the pen partition, figure 1. The intake air temperature was measured in the inlet and the room temperature was measured at 1.5 m height halfway the room above pen 8, the latter was used by the climate controller. The room temperature was

assumed to be equal to the air temperature in the outlet and used for the calculation of heat loss by ventilation. This assumption is checked with the cfd simulation, this is presented in the results section of this paper. All temperature data were recorded every 10 minutes.
The ventilation rate was measured by a measuring fan in the ventilation shaft measured ventilation in the room (accuracy < 50 m^3/h). The data were recorded every 10 minutes.
Carbon dioxide concentration was measured in the inlet air, in pens 3, 7 and 9 during two of the three selected hours. This was done from outside the room with a manual CO_2 sensor (Anagas CD 98, accuracy circa 50 ppm). After each other air samples were extracted from the room with a Teflon tubing system. Figure 1 shows the locations of the sampling points in the pen.
Video cameras were used to record animal lying locations in all pens. The pig location patterns were used to determine the locations of the sources of heat and carbon dioxide for the simulations.

Numerical simulations

Livestock test rooms used in published numerical simulation studies have usually been equipped with small air inlets that implied inlet velocities about 20 times higher than the velocities in the AOZ. Simulation of airflow in such rooms requires an intensive grid resolution in the air inlet zone (Bjerg et al., 2002a). Since the demand for computer power and calculation time highly depends on the used number of cells in the grid, it is important to be able to control the grid density in the different parts of air volume. A structured hexagonal grid (Bjerg et al., 2002a) includes a good possibility to control the grid resolution in different parts of the air volume. In the door-ventilation system differences between inlet velocities and velocities in the AOZ are small and, consequently, the ability to control the grid distribution in different parts of the room is not as important. Therefore the simulations in this study were based on an unstructured grid. The possibility to control the grid resolution is limited but the unstructured grid is able to handle air spaces with a complicated geometry.
The commercial Computational Fluid Dynamic program Fluent 5 (Fluent Inc) was used to perform the numerical simulations. To account for the effect of turbulence the k-epsilon turbulence model (Launder and Spalding, 1974) was chosen. This widely used model is relatively stable and it has proven to function well for simulations concerning indoor airflow. Both steady state and transient simulations were carried out. Time steps of 1 or 10 s and 5 or 10 iterations per time step were used in the transient calculations.

Geometry and grid construction

The geometry of the air space was constructed as a solid volume in the AutoCAD construction program from Autodesk. The geometry of a pig was represented by a half sphere (0.15 m radius), see figure 3. Using a model for each pig made it possible to adjust the location and magnitude of heat and carbon dioxide production to the actual conditions in each pen. The spherical shape had the advantage that the heat production could be distributed to only one surface per animal and it limited the risk of creating narrow air volumes between pig models requiring a locally high grid density. A plane surface on top of each pig model was used as inlet boundary for carbon dioxide, see figure 3. The area of the carbon dioxide inlet on the pig model was relatively large (0.009 m^2) which reduced the need for locally high grid resolution. The location of pig models was based on video recording of the pens. Figure 3 shows the location of pig models in case 3. Figure 5 shows location of pigs in all three cases. More details on the locations of pigs are given in the results section.

The pen partitions above the slatted floor close to the sidewalls consisted of 6 horizontal bars with 0.045 m spacing in between. A geometric modeling of these openings would be rather complicated and requires a local high grid density. Consequently it was modeled as a face with a defined flow resistance. To support the control of grid density the air volume above the pens was divided into three internal volumes (fig. 3) so it became possible to specify a finer resolution close to the surfaces compared to the middle of the room.

Using the ACIS format the geometry was exported from AutoCAD to the Gambit preprocessor from Fluent Inc. The preprocessor was used for boundary specifications and automatic grid construction. In each of the three cases the three-dimensional grid consisted of approximately 155 000 tetrahedral cells. Near the pens and close to the building surfaces the maximum cell dimensions were 0.15 m. In the middle of the air space the maximum cell dimension was 0.3 or 0.6 m. Figure 4 shows the grid distribution at one sidewall and in the symmetric plane of the room. The significance of grid distribution was not investigated in this study. The theoretical way to do this is to refine the grid until the solution no longer changes. But the practical possibilities to do so are restricted by computer power limitations.

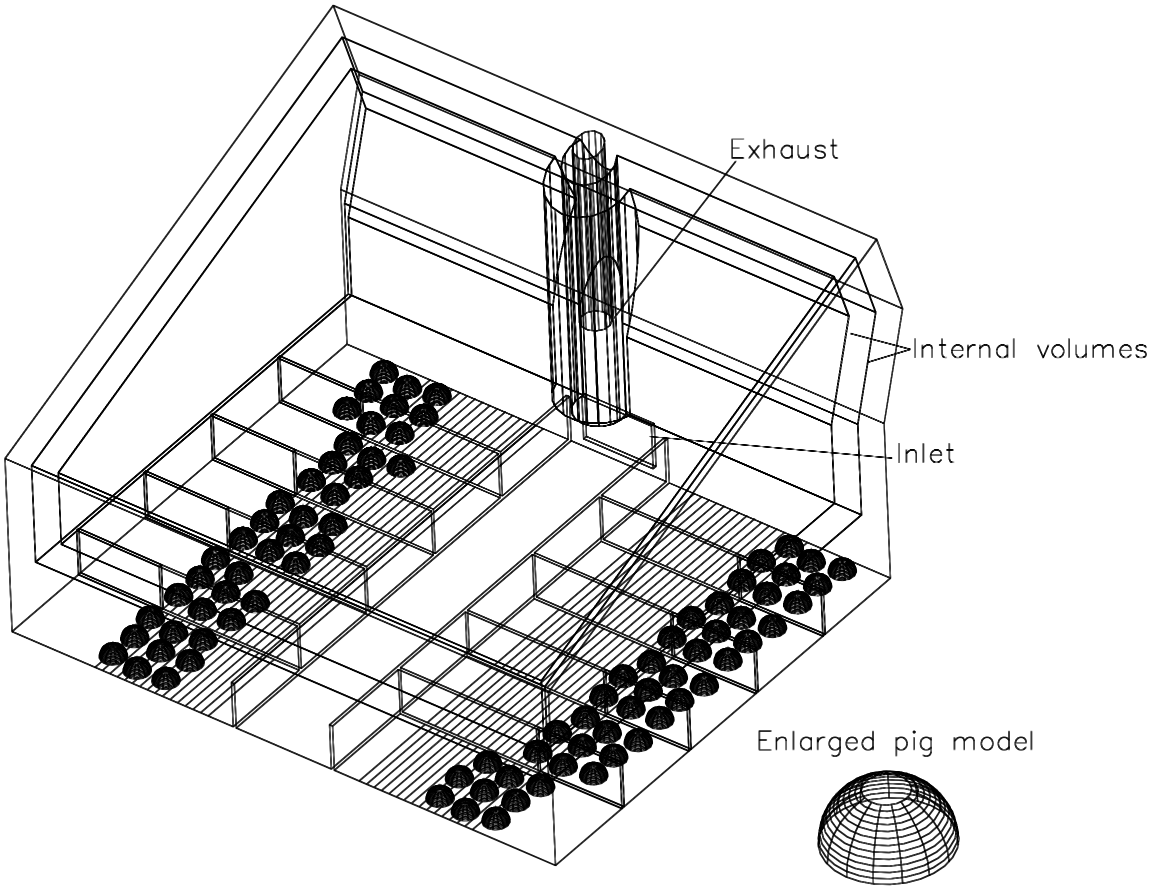

Figure 3. Geometry of air volume with location of pig models used in case 3.

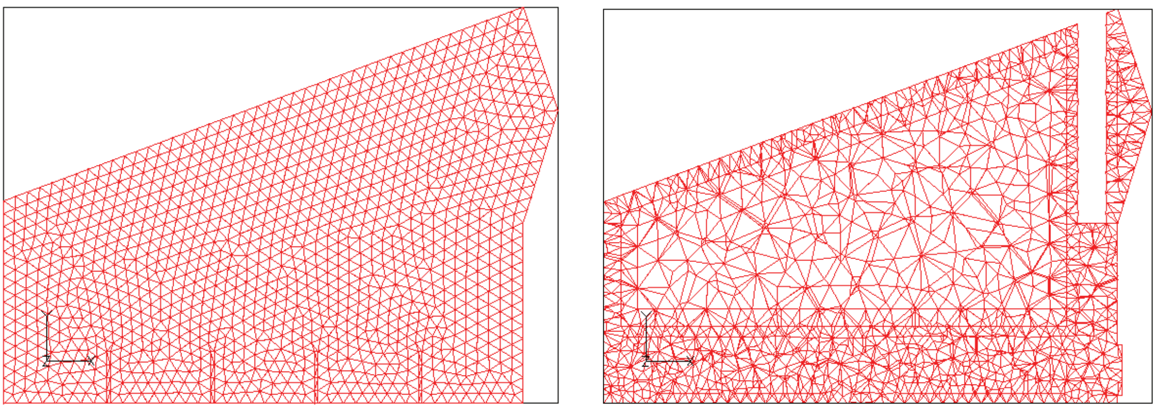

Figure 4. Grid distribution in the room, left at one side wall and right in the symmetric plane.

Table 1. Initial values and boundary conditions for simulation in case 1, 2 and 3.

	Case 1 27/5/2002 10.30 – 11.30	Case 2 27/5/2002 15.30 – 16.30	Case 3 28/5/2002 6.00 – 7.00
Ventilation (m^3/h)	649	912	449
Air inlet velocity (m/s)	0.338	0.475	0.234
Inlet air temperature (° C)	17.6	19.8	16.9
Heat supply from animals (W)	1634	1873	1067
Heat supply (W/animal)	17.0**	21.5	12.3

** to compensate for solar radiation 25 W extra was added to three pigs in each of the two pens close to the windows.

Heat balance

The airflow in the room was assumed to be driven mainly by the inlet air and the convective heat from animals. Consequently radiation from animal to room surfaces and heat transfer through building construction was not taken into account. There was no additional heating during the experiment. The heat balance was maintained by assuming that the convective heat from the animals was equal to the heat removed by ventilation, which was computed based on the measured inlet air temperature, the room temperature and the ventilation rate. The applied convective heat appears from table 1 and is in the magnitude of 40% of the expected total sensible heat production (calculated at 38 Watt, see earlier section in this paper) from the animals, the rest of the sensible heat loss is mainly radiation.

Boundary conditions

Air intake was specified as inlet air velocity homogeneously distributed over the inlet area and calculated from the ventilation rate as given in table 1. Carbon dioxide concentration in the inlet air was set to 300 ppm. Air outlet was modeled as *pressure outlet* and all surfaces were assumed to be impermeable for air and adiabatic (solid wall function). Animal convective heat supply was specified as heat flux (W/m^2) at the spherical surface area of the animal models. To compensate for observed solar radiation through windows, 25 W of extra heat supply was added to each of three pigs in the two pens nearest to windows (pen 9 and 10) in case 1. The 25 Watt was roughly estimated based on the sun-lighten surface (circa 0.3 m^2 per pen), on the direct solar radiation (at 27/5: 11.00 in The Netherlands this is circa 500 W/m^2) and on radiation losses of 50% in the dirty window. The flow resistance of the open pen partition near the side walls was determined in a separate numerical simulation model. Based on the simulated pressure drop Δp (Pa), the pressure discharge coefficient, C defined by: $\Delta p = C\frac{1}{2}\rho v^2$ (Fluent, 1998) was determined to be 1.76 where ρ air density (kg/m^3) and v air velocity (m/s),

CO_2 production from each animal was calculated as 16.3 liter/h of CO_2 per 100 W total heat production (CIGR, 1984). For the actual average pig weight of 13.1 kg CO_2 production was calculated at 9 liter of CO_2 per hour per animal. This quantity of CO_2 was added as a velocity inlet into the air volume at the top of each of the 87 pig models in the simulation.

Results and discussion

Measurements

Results of the measurements on air velocity, air temperature, ventilation rate and CO_2 concentration at the measuring positions (fig. 1) in the three periods are presented in table 2. In all three pens air velocity in the z-direction contributed most to the air velocity magnitude. Air velocity in pen 3 was similar for the three periods, despite differences of the ventilation rates. Air velocity in pen 9 varied the most within the 1-hour periods and between the 3 cases. In case 1 and 2, the calculated increase in CO_2 concentration compared to the inlet was lowest in pen 9 and highest in pen 7.

In case 1 the outside temperature during the 1-hour period raised almost 2° C. The room temperature raised 0.6° C and ventilation rate increased by 170 m^3/h. Surprisingly, the air velocities in the three pens reduced during the 1-hour period, which means higher ventilation resulted in a lower air velocity at the measuring positions in the pens. In case 1 there was some direct solar radiation in pens 9 and 10 during the first 40 minutes. In case 1 and 2, the warmest pens were pens 3 and 4. In case 3 the temperatures in the pens on the right side of the operator walkway were somewhat lower than on the left side. This was caused by the location of the animals as they lay further to the back of the pen on the slatted floor (fig. 5). In case 3 the ventilation was constant and at minimum level.

Table 2. Average of ventilation rate, air velocity, temperature and CO_2 concentration measurements and standard deviation.

		Case 1		Case 2		Case 3	
		Average	Stdev	Average	Stdev	Average	Stdev
Ventilation (m^3/h)		649	70	912	52	449	0[a]
Air velocity (m/s)							
Pen 3	x-direction	-0.04	0.02	-0.03	0.01	-0.03	0.01
	y-direction	0.02	0.01	0.02	0.01	0.02	0.01
	z-direction	0.10	0.01	0.10	0.01	0.12	0.01
	Omnidir.	0.11	0.02	0.11	0.01	0.12	0.01
Pen 7	x-direction	-0.01	0.02	0.02	0.02	0.00	0.02
	y-direction	0.03	0.02	0.02	0.01	0.01	0.01
	z-direction	0.08	0.01	0.10	0.01	0.09	0.02
	Omnidir.	0.09	0.01	0.11	0.01	0.09	0.02
Pen 9	x-direction	0.03	0.01	0.02	0.02	0.02	0.01
	y-direction	0.01	0.01	0.03	0.03	0.02	0.01
	z-direction	0.06	0.03	0.12	0.03	0.06	0.01
	Omnidir.	0.07	0.02	0.13	0.03	0.07	0.01
Temperature (°C)							
Outside		18.0	0.7	22.6	0.7	13.0	0.2
Inlet		17.6	0.2	19.8	0.2	16.9	0.1
Climate controller		25.1	0.2	25.9	0.1	24.1	0.1
AOZ	Pen 1	23.2	0.2	24.2	0.3	22.7	0.1
	Pen 2	23.4	0.3	24.3	0.1	23.3	0.1
	Pen 3	24.2	0.6	25.0	0.3	22.8	0.2
	Pen 4	24.2	0.4	24.9	0.2	23.4	0.1
	Pen 5	23.5	0.6	24.5	0.2	22.6	0.1
	Pen 6	23.4	0.4	24.6	0.2	23.3	0.2
	Pen 7	23.3	0.3	24.6	0.3	22.0	0.1
	Pen 8	23.1	0.5	24.6	0.2	23.5	0.1
	Pen 9	21.4	0.2	22.5	0.4	22.2	0.1
	Pen 10	22.7	0.5	23.9	0.2	23.0	0.3
Increase CO_2 concentration (ppm)							
	Pen 3	268	155	431	104	n.a.	n.a.
	Pen 7	313	161	523	256	n.a.	n.a.
	Pen 9	185	38	206	98	n.a.	n.a.

[a] ventilation was constant
n.a. = not available

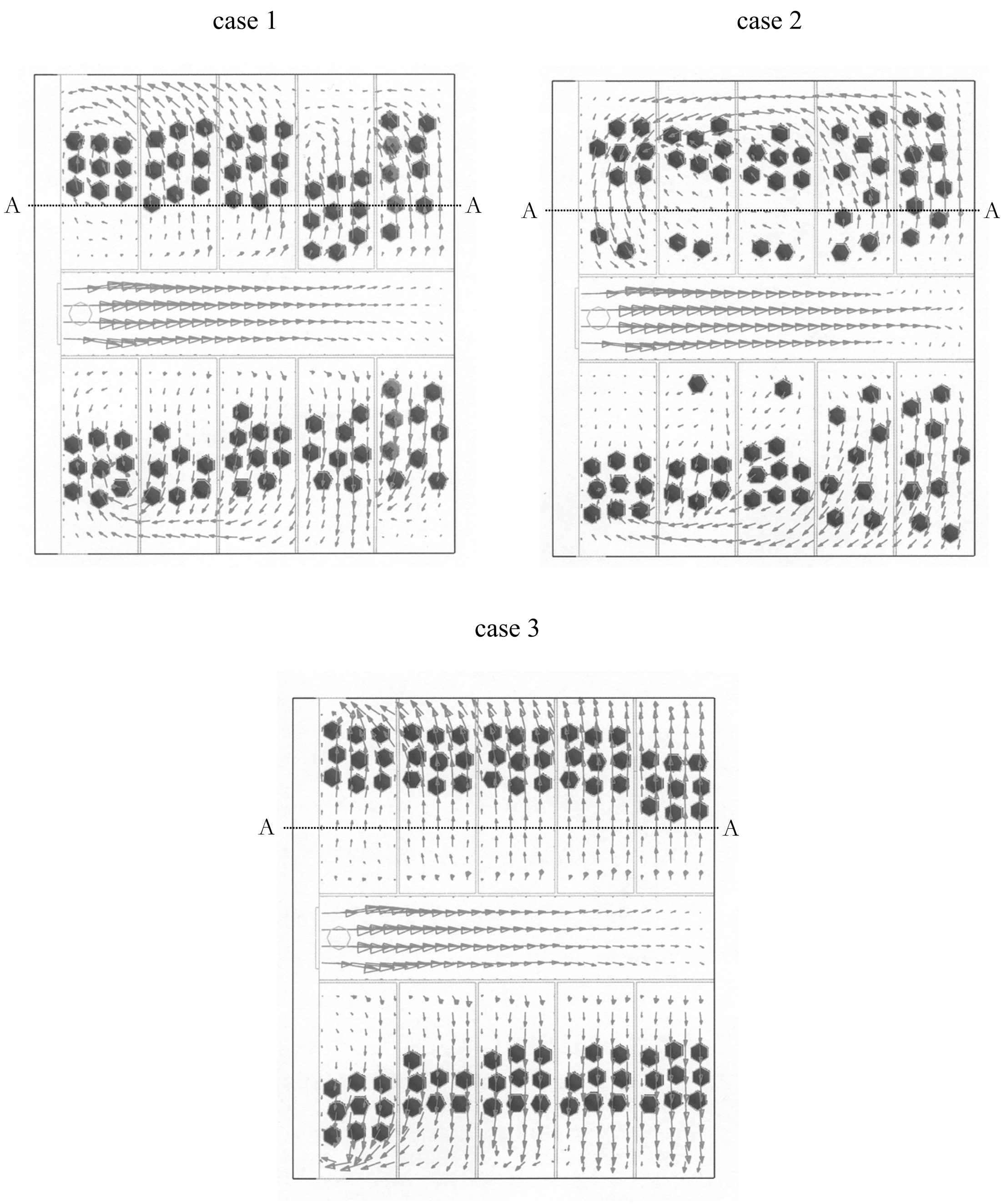

Figure 5. Location of pig models and simulated airflow 0.3 m above the floor in case 1, 2 and 3.

Video recordings were analyzed to determine locations of the animals. The results are presented in figure 5 in the next section. In case 1 most of the piglets in all pens were lying on the back part of the solid floor. In pens 9 and 10 they had a preference for lying in the area with solar radiation. In pen 7 they were in the front of the pen, on the solid floor. In case 2 the piglets were more active. For pens 7, 8 and 10 it was not possible to indicate any specific location for the animals, so the heat and CO_2 sources are randomly distributed in the simulations. In case 3 the piglets in pens on the left side of the walkway were lying on the back side of the solid floor and on the slatted floor. On the right side of the walkway they were lying more on the solid floor.

Numerical simulation

The steady state simulations did not converge into stable solutions and therefore the presented results are based on the transient simulations that gave stable solutions with both 1 and 10-second time steps and both 5 and 10 iterations per time step.

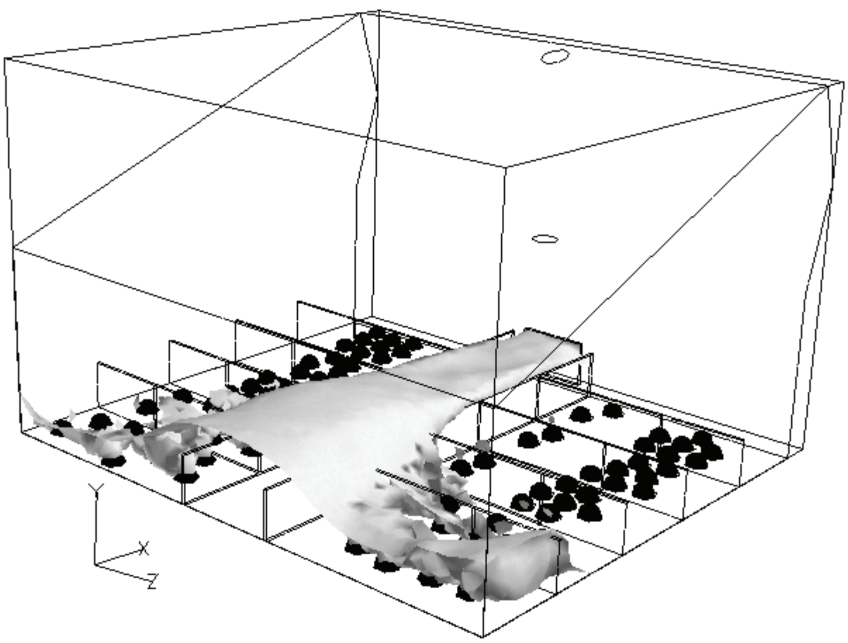

Figure 6. Simulated CO_2 concentration in case 2; the iso-plane shows the 700 ppm level (400 ppm above inlet concentration).

The simulated airflow pattern 0.3 m above the floor (fig. 5) shows that the airflow in the AOZ was mainly z direction from the operator walkway to the sidewalls. Figure 5 shows that the variations in inlet velocity, heat supply and locations of pigs resulted in different airflow patterns in some of the pens, e.g. the airflow direction in pen 1 changed 180 degrees from case 2 to case 3. In case 3 the airflow in all pens is orientated parallel away from the walkway. Figure 6 shows the calculated 700 ppm carbon dioxide 3-dimensional iso-plane in case 2. The CO_2 concentrations were lower than 700 ppm under the iso-plane, and higher than that above the iso-plane. Figure 6 illustrates that in pens 9 and 10 the CO_2 concentration was lower than in the other pens, which indicates that most of the fresh air enters the pens farthest from the door inlet.

Comparison of simulation and measurements

Air velocity

Both measurements and simulation showed that the airflow at the measuring points in pens 3, 7 and 9 in all three cases was oriented in the direction from walkway towards the side wall of the room. The air velocity in this direction (positive z) contributed most to the air velocity magnitude in all the measurements and in the simulated air velocities at the measuring points in all the cases.

The measured air velocity in the z direction and the calculated vertical velocity profiles around the measuring points are shown in figure 7. It shows that the simulated velocities agree with measurements in pen 7 in case 2 and in pen 9 in case 3. For the rest the differences were larger, and reached up to a substantial 0,05 m/s. In case 2 the simulation shows that there is much difference in air velocity between the pens contrary to the measurements.

An explanation for the differences could be that objects in the pen are not taken into account in the model. The first thing to add is probably the feeder. In addition, it is possible that the air velocity profile is shifted upward or downward because of airflow obstruction caused by standing animals. This has a pronounced effect on the air velocity at 0.3 m height, the simulated vertical air velocity profile indicates a large velocity gradient above the floor and shows that the airflow direction changes at approximately 0.5 m above the floor and becomes directed towards the operator walkway. This gradient agrees very well with the velocity profile as measured in the experimental room in earlier research (Van Wagenberg and de Leeuw, 2003), as is described in the materials and methods section in this paper. This similarity in air velocity profile illustrates that simulations can predict realistic values for air velocity in the AOZ.

Due to the big spatial variation for air velocity within the AOZ, sensors used for validation experiments should be located in such way that patterns can be visualized and compared with the simulation rather than unstructured point measurements.

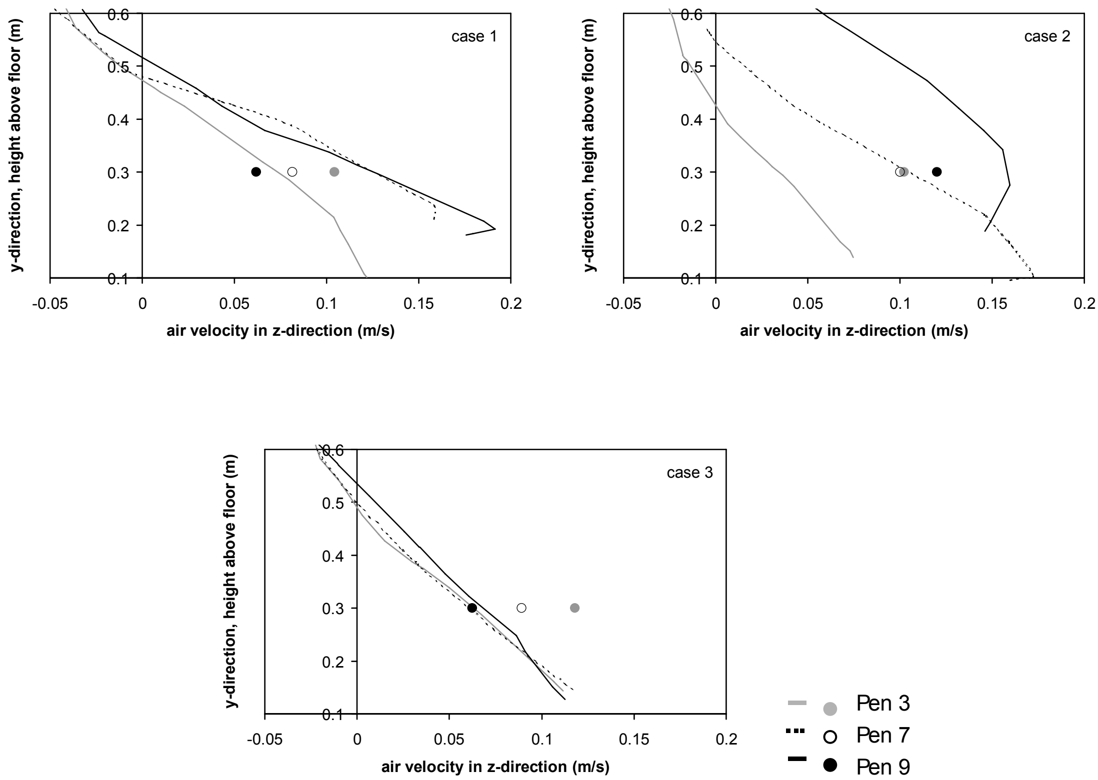

Figure 7. Comparison of three simulated air velocity profiles (lines) (pen 3: x = 4.2 m, y = 0 – 0.6 m and z = 1.6 m; pen 7: x = 1.8 m, y = 0 – 0.6 m and z = 1.6 m; pen 9: x = 0.6 m, y = 0 – 0.6 m and z = 1.6 m) and three local air velocity measurements.

Temperatures

In table 3 some results of temperature recordings and simulation are shown. The simulated temperature differences between the location of the climate controller temperature sensor and the outlet were small (0 – 0.2° C). This is important for the simulations in which those temperatures were assumed to be equal.

Table 3 also shows that the simulated temperatures in the outlet were lower than the measured temperatures by the climate controller. This difference was surprising, because the heat supply in the model was based on the measured heat removed by ventilation. The explanation seems to be that the heat supply in the model was smaller than assumed because the grid generation converted the spherical pig models to edged figures with smaller surface areas.

Table 3. Results of temperature measurements and simulations.

	Temperature (°C)		
	Measured by Sensor Climate Controller	Simulated at Location Climate Controller	Simulated in Outlet
Case 1	25.1	24.2	24.3
Case 2	25.9	25.3	25.3
Case 3	24.1	23.1	23.3

In figure 8 simulated temperature profiles and measured temperatures at y=0.15 m in the AOZ are shown. In most cases the simulated AOZ air temperatures are equal or lower than the measured temperatures. A minor reason for this difference might be the difference between the assumed and the effective heat supply area. Another reason is probably due to the radiation heat transfer was neglected in the simulations by assuming all surfaces to be adiabatic. In the real room the animals transmit radiation heat to the pen partitions and building surfaces. The building surface, especially the ceiling, retransmits some of this heat to the relatively cold floor areas in and close to the walkway. Pen partitions and floor surfaces also transfer convective heat to the entering air, before it reaches the location of the temperature measurements.

Generally the simulated temperature increases from the pens 9 and 10 to pens 1 and 2, which agrees with figure 6 that indicates that most of the fresh, cold air enters the pens farthest from the door inlet. However, in the measurements the temperatures in pens 1 and 2 were lower than in pens 3 and 4. A possible explanation for this difference is that the surface temperature of the wall next to the central alley is relatively low due to a low degree of insulation. Consequently the air in pens 1 and 2 deliver heat to the wall, which is not accounted for in the simulation.

The comparison between simulations and measurements is relatively poor. This indicates that the further development of the simulation model with the suggested items is necessary to improve the quality of the predicted temperatures in the AOZ.

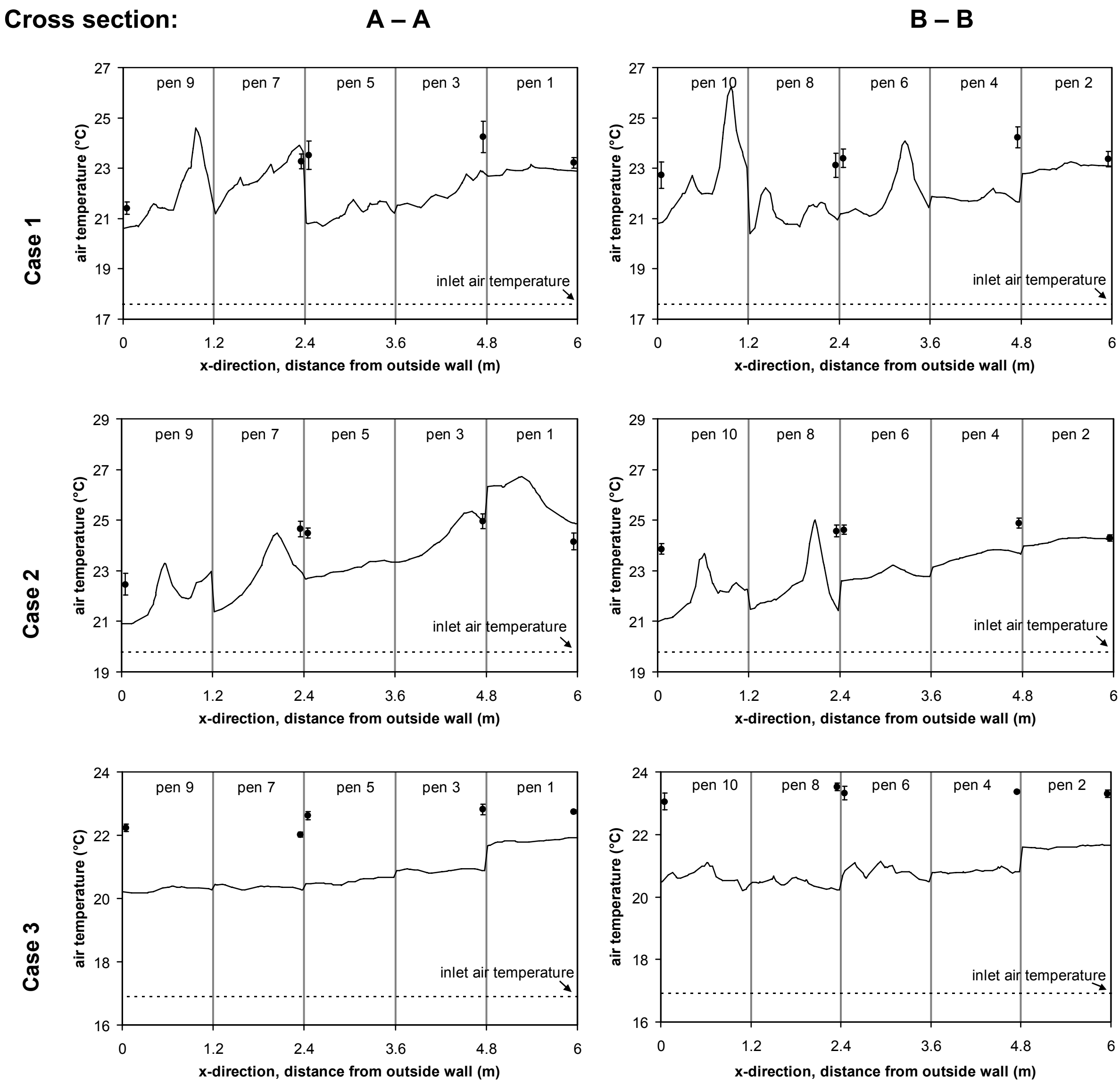

Figure 8. Comparison of two simulated temperature profiles (black line) in the cross sections A-A and B-B (see figure 1) at y = 0.15 m with local temperature measurements with standard deviation ( ) and temperature of the inlet air.

CO_2 concentrations

Figure 9 compares simulated and measured carbon dioxide concentration 0.15 m above the floor in the AOZ (z=1.6). In case 3 there were no measurements. The shown profile is located very close to the release area of carbon dioxide from some of the pig models especially in cases 1 and 2 (see cross section A – A in figure 5). Consequently very high carbon dioxide concentration was predicted close to these models and the value is not shown in figure 9. The comparison shows that the simulated values are higher than measured, in case 1 and in case 2 in pen 3. But it is not possible to decide whether the measurements or the simulation is the main source for this deviation. In all cases the simulated carbon dioxide concentration increased from the pens close to the outside wall to the pens close to the opposite wall. A higher ventilation rate resulted in an increased difference of the concentration between the pens. This relationship between inlet velocity and air distribution between pens in the door-ventilation system agrees with earlier experimental work reported by Van Wagenberg and Smolders (2002).

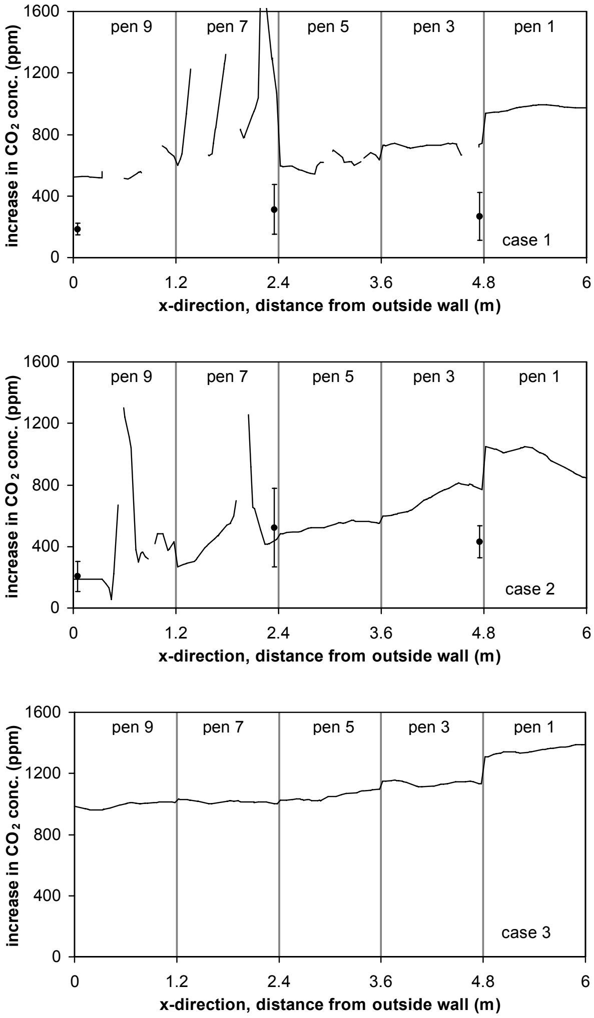

Figure 9. Comparison of simulated carbon dioxide profiles (black line) in the cross section A-A (see figures 1 and 5) at y = 0.15 m with local carbon dioxide measurements with standard deviation (⧳), the simulated CO_2 values close to the pig simulators are removed.

Conclusion

Measurement of one-hour average air velocity, air temperature and carbon dioxide concentrations in a room with live pigs can generate data for validation of numerical simulation based on stationary boundary conditions. The used unstructured grid construction method was an appropriate way to handle the complicated geometry (including a model of each animal) in the door-ventilation system.

The simulated air velocity profile above the solid floor agreed fairly well with expectations based on earlier research, comparison of the locally measured and simulated air velocities showed some good correspondences as well as some substantial differences. Adding the feeder in the model is expected to give an improvement. Due to the big spatial variation for air velocity within the AOZ, sensors used for validation experiments should be located in such way that patterns can be visualized and compared with the simulation rather than unstructured point measurements.

For temperature in the AOZ the differences between simulation and measurement were substantial. Including exchange of heat radiation is expected to be an important improvement of the simulation model. Other improvements could be a more detailed specification of inlet condition, e.g. including a space in front of the inlet, see Bjerg et al (2002a) or using a significantly denser grid which dramatically would increase the needed computer power and calculation time.

The study confirms the expectation that numerical simulation has the potential to become an important tool for designing and improving ventilation systems for livestock rooms. In connection to the door-ventilation system the study confirms that the air distribution is inhomogeneous especially at high ventilation rates. In the pens closest to the door the CO_2 concentration and temperature is highest. Numerical simulation can be used to improve the air distribution in a further development of this ventilation system.

Acknowledgements

The authors wish to acknowledge the funding provided for this project by the Dutch Product Boards for Livestock, Meat and Eggs and the Dutch Ministry for Agriculture, Nature Management and Fisheries. The authors thank Mr. Mark de Leeuw, Researcher Engineer at the research Institute for animal Husbandry, for his technical assistance during the project.

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CHAPTER 6

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.

Introduction

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 Somlders, 2002). 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 Somlders, 2002). 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 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 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).

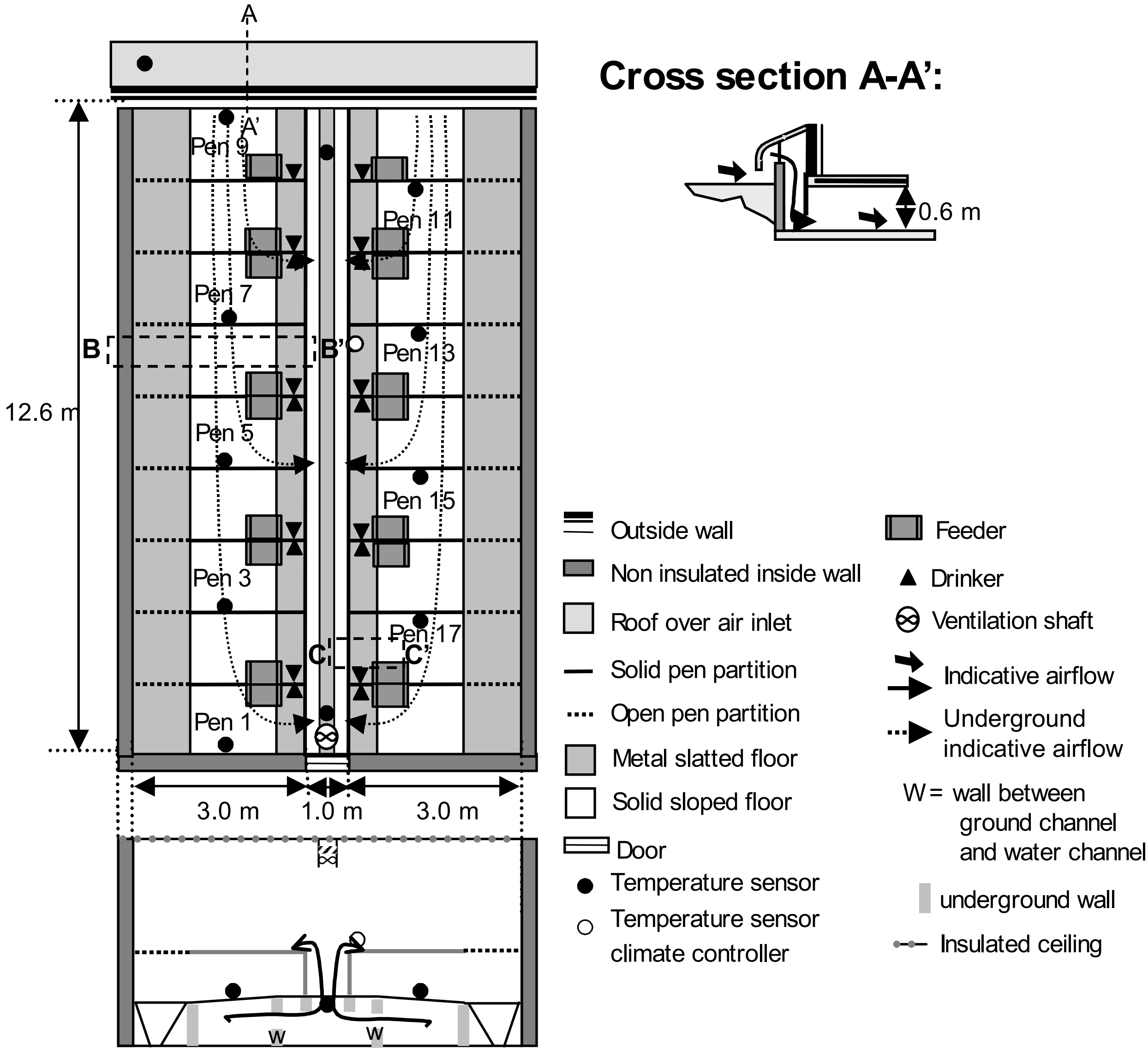


Figure 1. Plan view of the experimental room showing the pens (not all pen numbers are shown), airflow, and locations of the temperature sensors (not to scale). Cross-section A-A' is a detail of the air inlet. Cross-sections B-B' and C-C' are shown in figure 2.

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.

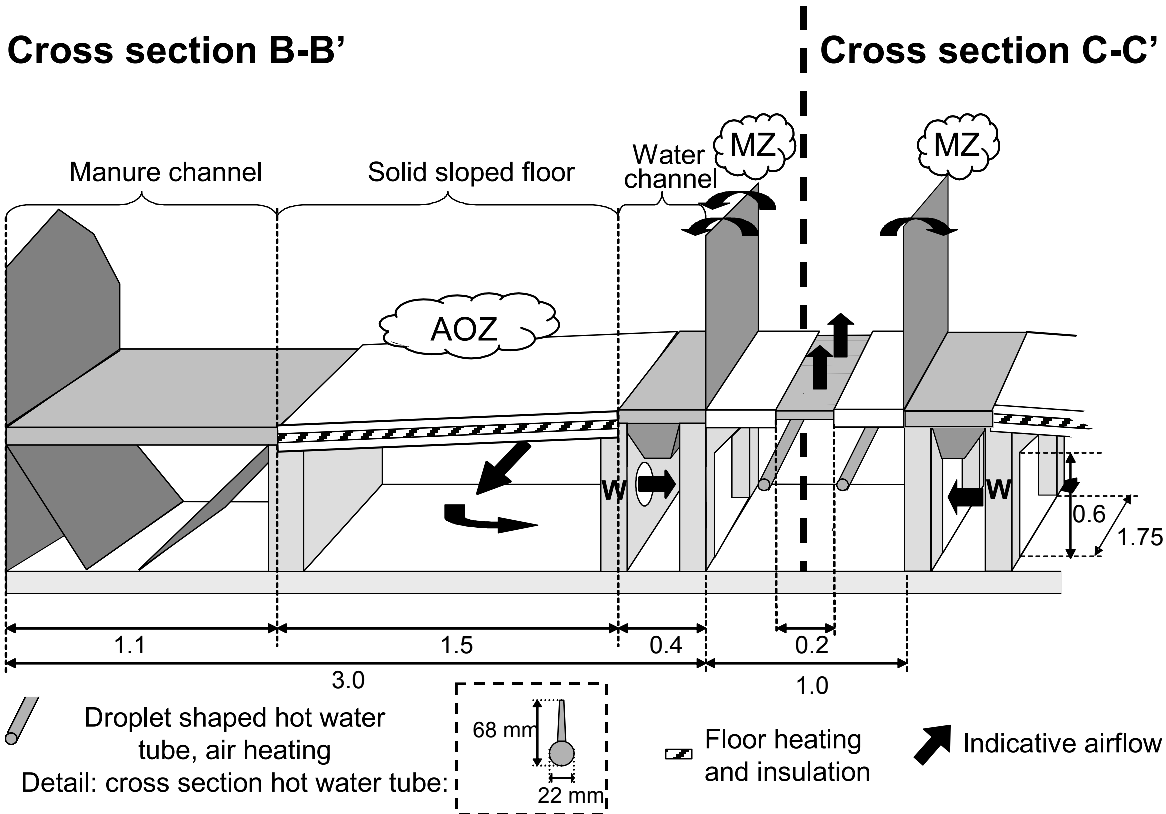
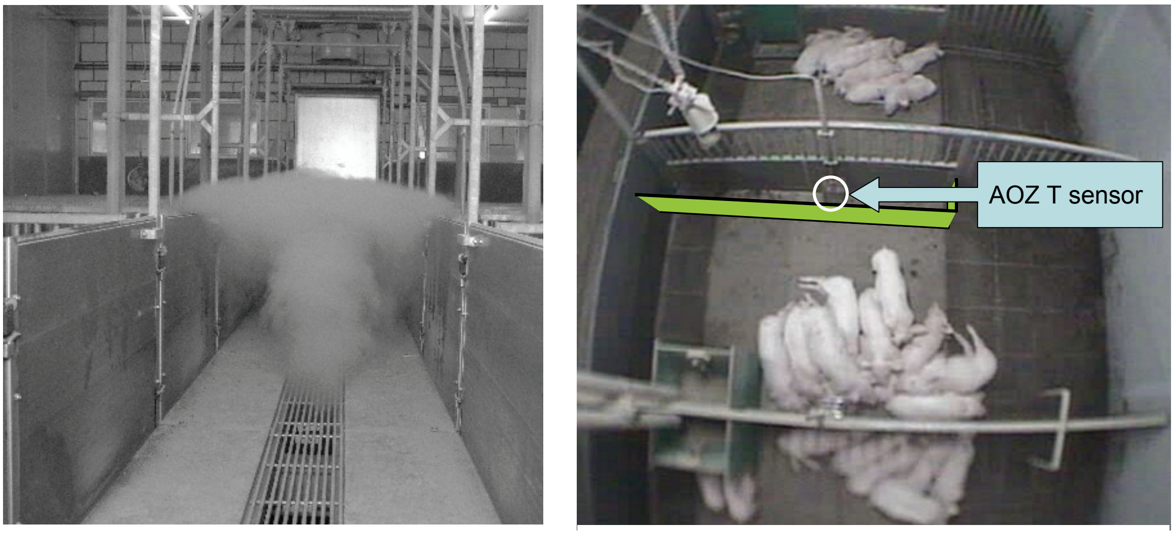


Figure 2. Cross-sections B-B' and C-C' of the ground channel (fig. 1) showing the animal-occupied zone (AOZ) and mixing zone (MZ) where sensors were located. The detail cross-section shows a heating tube. All dimensions in m (not to scale).

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 under floor 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).



(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).

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 temperature, 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 set point, 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 set point, 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.

Table 1. Climate settings for the experimental room.

	Temperature (°C)			Ventilation per Piglet ($m^3 h^{-1}$)[a]	
Day	Air Heating	Floor Heating	Ventilation Set point	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

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.

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:

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

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 set point 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:

$$\mathrm{SSG}_i = \frac{b_{0i}}{1+a_1} = \frac{\Delta y}{\Delta u_i} \quad \mathbf{(2)}$$

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:

$$\tau = \frac{-\Delta t}{\ln(-a_1)} \quad \mathbf{(3)}$$

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 set points 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 measured room temperature.

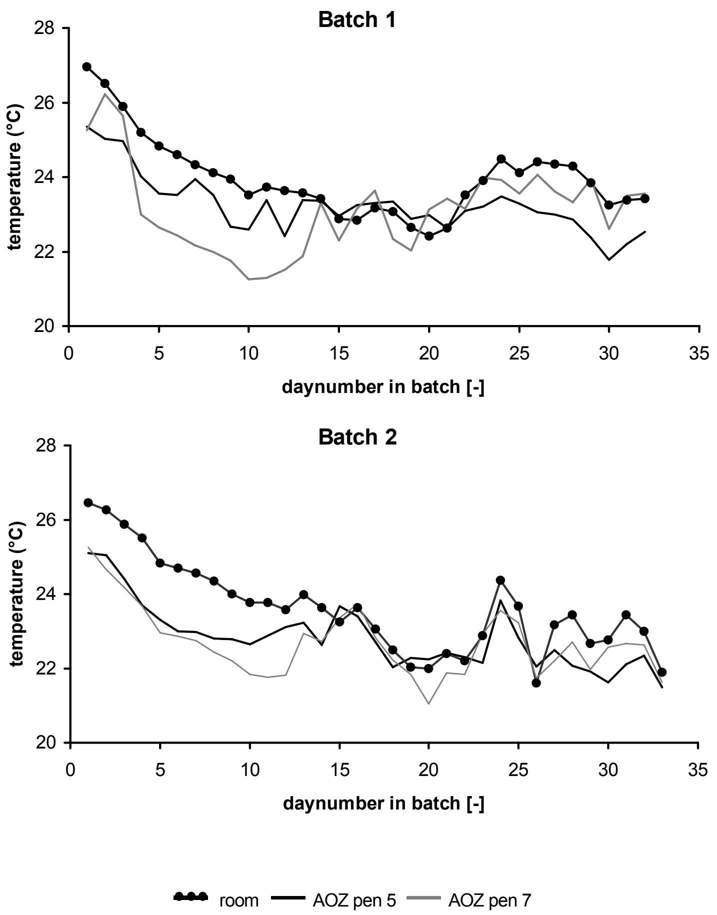


Figure 5. Daily average room temperature and AOZ temperatures measured in pens 5 and 7 during batches 1 and 2**.**

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.

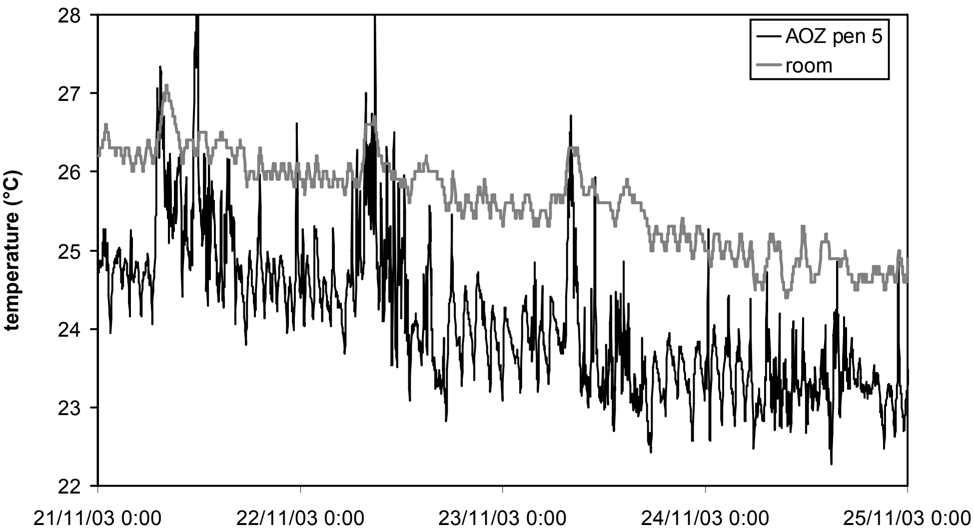


Figure 6. AOZ temperature in pen 5 and room temperature during the first 4 days of batch 2 (measured every 2 min).

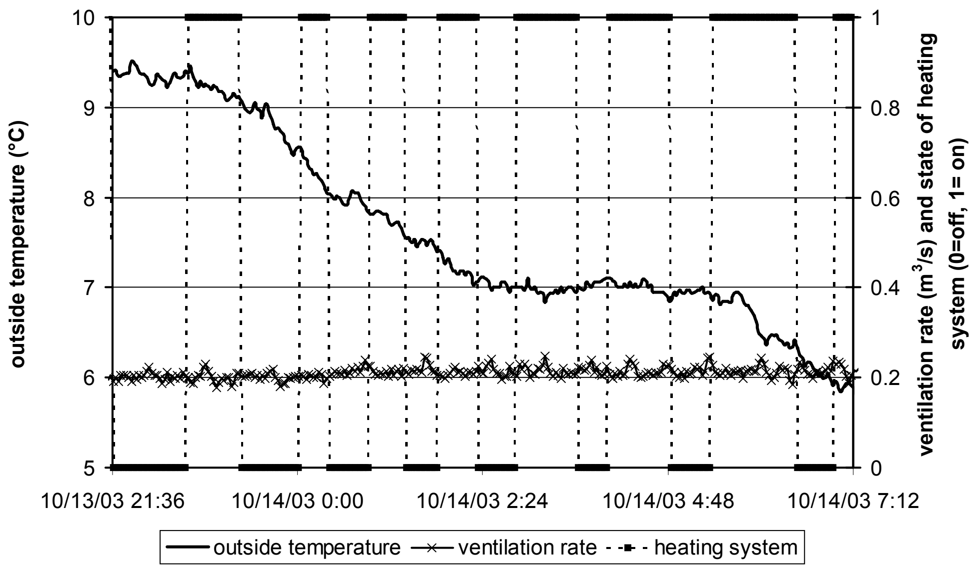
The generally lower temperatures in the AOZ indicate that there was more fresh air in the AOZ than around the sensor in the MZ. When the incoming air was relatively cold (compared to room air), a thin layer (several centimeters) of fresh air flowed over the pen partition; the controller sensor in the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

Model-Based Predictive Controller

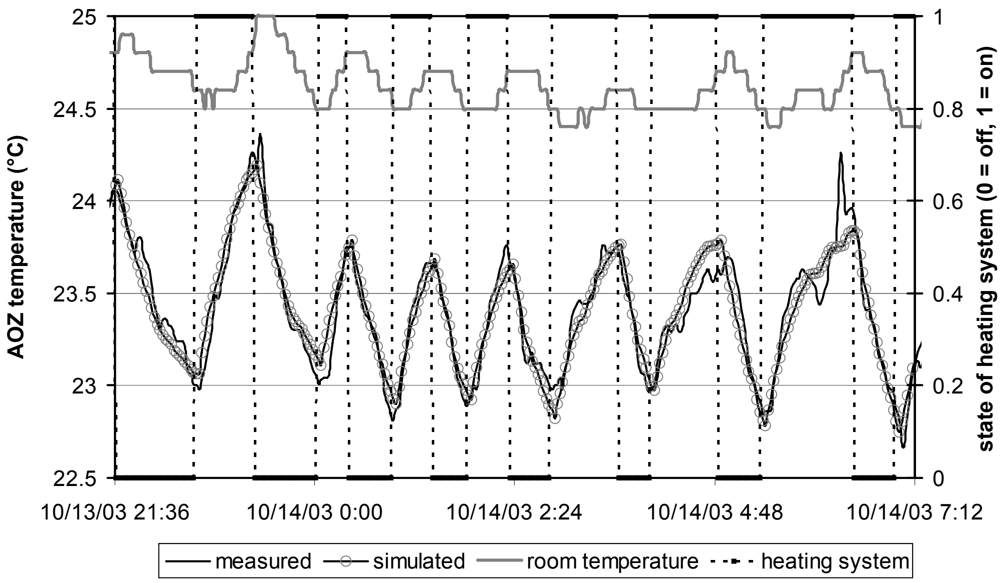
Figure 7 shows an example of the course of the model inputs (i.e., outside temperature, ventilation rate, and state of the heating system) and output (both measured and simulated AOZ temperature) of the model (pen 9, dataset 4). The simulated AOZ temperature will be addressed later in this article.

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.



(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).

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.

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.

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]			Avg
				Ventilation Rate, b_{01}			Outside Temp., b_{02}			State of Heating, b_{03}						
		a_1		ATD	Avg	Avg	ATD	Avg	Avg	ATD	Avg	Avg				τ
Pen	Avg R_t^2	Avg	SE	(min)	b_{01}	SE b_{01}	(min)	b_{02}	SE b_{02}	(min)	b_{03}	SE b_{03}	SSG_1	SSG_2	SSG_3	(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 [-]$^{-1}$).

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]			Avg
				Ventilation Rate, b_{01}			Outside Temp., b_{02}			State of Heating, b_{03}						
Data	Avg	a_1		ATD	Avg	Avg	ATD	Avg	Avg	ATD	Avg	Avg				τ
Set	R_t^2	Avg	SE	(min)	b_{01}	SE b_{01}	(min)	b_{02}	SE b_{02}	(min)	b_{03}	SE b_{03}	SSG_1	SSG_2	SSG_3	(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 [-]$^{-1}$).

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 set point 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 set point 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 set point. After 4 h, the calculated AOZ temperature became lower than the set point 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 in figure 8b. In figure 8a, the AOZ temperature with the MBP controller shows quicker and smaller fluctuations and stays closer to the set point 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 set point 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.

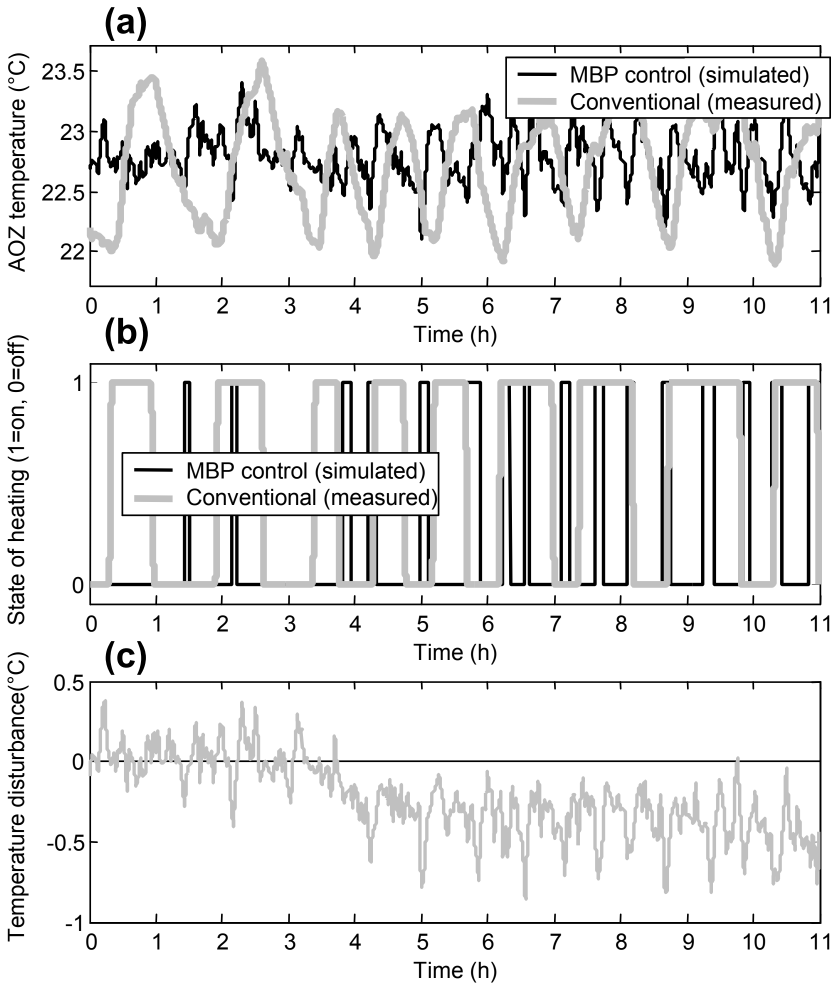


Figure 8. Inputs and output of the controller (pen 7, set point 22.72°C): (a) AOZ temperature, (b) state of the heating system, and (c) temperature disturbance. Black lines represent the simulated MBP control system, and grey lines are based on measurements with the conventional control system.

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 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 set points, 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.

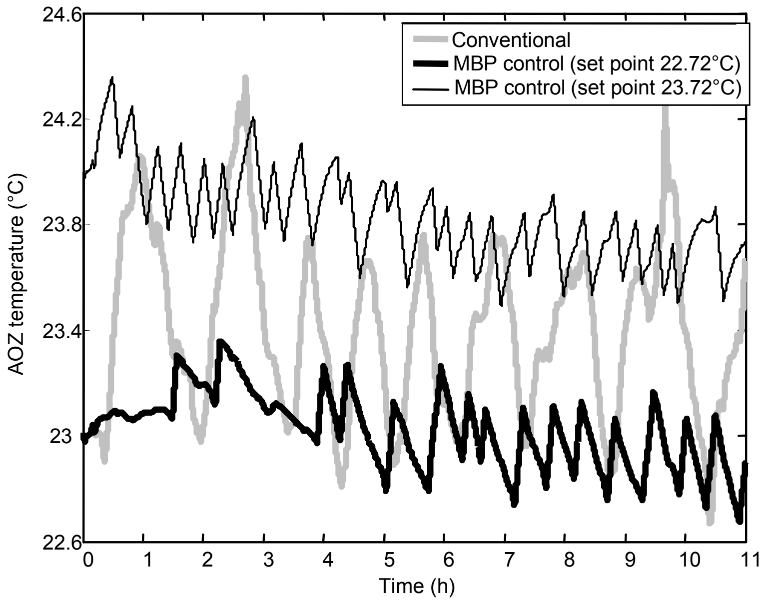


Figure 9. Course of the AOZ temperature in pen 13 (dataset 4) with conventional control (gray line) and MBP control (black lines) using the controller sensor in pen 7 with two different set points.

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 set points. The standard deviation is a good indicator of AOZ temperature stability in this situation, because the controller had a constant set point and because there were some differences in temperature between pens.

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 set points (sensor in pen 7) during the 11 h period.

	Conventional (Set Point in MZ was 24°C)		MBP control (Set Point in AOZ was 22.72°C)		MBP control (Set Point 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

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 set points (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 set point 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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Chapter 7

General Discussion

Set-up of the study

The right climatic conditions are of extreme importance for weaned piglets. This thesis shows that in this respect the focus has to be on the AOZ (Animal Occupied Zone) climate or microclimate, instead of on the macroclimate. In various ways this research contributes to the insight into and the potential improvement of the AOZ climate in rooms for weaned piglets. Moreover it presents tools for research and development of new ventilation systems in pig houses:

- by presenting and testing systems and strategies for climate measurements in the AOZ,
- by determining the effects of air inlet systems on AOZ climatic variables,
- by providing criteria for the evaluation of the performance of different ventilation systems with respect to optimum thermal conditions in the AOZ,
- by building and calibrating a Computational Fluid Dynamics (CFD) model enabling an accurate prediction of the spatial distribution of the AOZ climate,
- by developing a climate control system including AOZ temperature measurement.

Experiments described in this thesis were conducted under normal farming conditions in fully operational rooms with weaned piglets. No treatments were imposed other than regular farm management practices. This approach ensures that the outcome of the research is highly useful for practical applications. The insight gained into the AOZ conditions in the experimental rooms of this study may in many cases be generalized to statements about rooms with similar ventilation systems in practice, thereby becoming applicable for pig husbandry. A drawback of this approach was that there were some uncontrolled experimental conditions, such as weather conditions, animal health status and uniformity of batches. As a result, some of the outcome of experiments have to be regarded as specific for the prevailing circumstances, while translation to other situations may be difficult. This was the reason for a critical data selection in chapter 4. Other approaches in AOZ climate studies, such as simulations (chapter 5; Hoff et al., 1992; Hoff et al., 1995; Puma et al.,1999; Bjerg et al., 2000; Zhang et al., 2000) and experiments in laboratory test rooms without animals (Randall, 1980; Ogilvie et al., 1990; Hoff, 1995, Maghirang et al., 2000), do not have this disadvantage, and can also be done cheaper and faster. However, a characteristic of these approaches is the need to make simplifications so it is not known how well it predicts the real situation, preventing the direct applicability of the conclusions for practical farming. As an example, the presence of living pigs in a real-scale situation influences the mixing of air in a room and thus affects the climatic zones and conditions in the AOZ (Smith et al., 1999). The dynamics of conditions in the AOZ are difficult to find from model studies and simulations only.

To improve the AOZ climate all approaches are valuable. Simulation and modeling are especially needed for designing new ventilation systems, whereas measuring under farming conditions is needed to calibrate the models and evaluate the systems. The discussion below is structured around measuring, evaluating and controlling the AOZ climate.

Measuring the AOZ climate

The focus was on three AOZ climatic variables: air temperature and air velocity as indicators of thermal comfort, and the CO_2 concentration as an indicator of air quality. Though, at concentrations encountered in pig rooms CO_2 itself being a non-harmful gas, it is a good measure of fresh air supply to the AOZ and therefore may also be an indicator of other contaminant concentrations at animal level such as vapor, dust, and ammonia. However, a difference between CO_2 and other contaminants such as dust and ammonia is that the animals are the main source of CO_2, where as the other contaminants originate mainly from other sources.

Most of the measurements in this study were done on a continuous basis and automatically, avoiding persons from entering the room for performing measurements, what considerably eliminates disturbances of the outcome of measurements. Apart from the measuring range, no specific demands apply to the temperature and CO_2 sensors that can be used. For measuring air velocity under AOZ conditions, an ultrasonic anemometer proved to be an accurate and usable instrument, giving insight into the time pattern of air velocity, the spatial distribution of air velocity and the air-flow direction (chapter 3).

The three climatic variables in a pig room are interrelated. Normally, at locations in the AOZ with a large amount of fresh air, both air temperature and CO_2 concentration are expected to be relatively low, with the air velocity being relatively high. Such pattern is clearly seen in the door-ventilated room, where the pens in the back had the highest air velocities and the lowest temperatures (chapter 4). They also show the lowest CO_2 concentration (chapters 2 and 5).

In this study the AOZ temperature appeared to be the most critical climatic variable under the circumstances of the experiments conducted. In the experiment of chapter 4 the added value of air velocity measurements to predict thermal comfort was found to be limited, despite significant differences in air velocity between pens (chapter 3). Analyzing the AOZ kata-value (*KV*), which combines air velocity and air temperature, revealed that the air temperature in general was the most important variable determining the actual range of *KVs* and not the variation in air velocities (chapter 4). Furthermore, the air temperature distribution is known to give information on the fresh air distribution in a room with internal heat load (Boonen et al., 2002), with the air temperature to be measured easier and cheaper than the air velocity and CO_2 concentration.
Regarding the previous lines, it can be concluded that the temperature is the first variable to be taken into account when changing the focus from macroclimate to microclimate, without denying the known relevance of air velocity (Pyykkönen, 1992; Tao and Xin, 2003) and air quality (Drummond et al., 1980; Madec et al., 1998; Wathes et al., 2002; Wathes et al., 2004). This study also reveals that the inclusion of air velocity and CO_2 measurements has surplus value, as the spatial distribution patterns of temperature, air velocity and CO_2 concentration in the entire room and within pens are found not to be similar (chapters 2, 3 and 5). Sources and sinks of heat and CO_2 are different and the local air velocity can be influenced by vortices. In other ventilation systems, for example systems with air recirculation (that were not included in the study), the relative importance of air velocity is probably larger. Therefore, it is recommended to keep air velocity and CO_2 concentration as reference measurements in AOZ climate control.

It was found that animals close to the sensor could disturb the AOZ measurements (chapter 6). This aspect was ignored in chapters 2 to 5. In any future studies, the sensors need to be mounted in enclosures to prevent the warm bodies of the piglets from influencing the AOZ measurement directly by radiation or conduction, or indirectly by obstructing the flow of fresh air to the sensor. Also, the sensors need to be positioned in such a way that they do not affect the pig's behavior by attracting too much of their attention.
Positioning the temperature sensor for climate control near or inside the AOZ is especially advantageous in rooms with a relatively large spatial temperature variation, and thus in rooms

with displacement ventilation (Maghirang et al., 2000). In rooms with ground channel ventilation, fresh air flows relatively directly into the AOZ causing temperature differences between microclimate and macroclimate. The AOZ temperature was found to be very sensitive to fluctuations in the inlet temperature (chapter 6). Earlier we suggested to create a special narrow sensor pen without animals in a ground channel ventilated room (chapter 6), in order to optimally measure and control the temperature of air flowing towards or around the animals.

Evaluating the AOZ climate

Ventilation and climate control systems are intended to meet the animals' climatic demands by minimizing the occurrence of periods with a sub-optimum climate as these are expected to reduce animal performance, welfare and health and can cause pen fouling (Le Dividich and Herpin, 1994; Scientific Veterinary Committee, 1997; Aarnink et al., 2001). As stated earlier, the AOZ thermal conditions should be within the Thermo Neutral Zone (TNZ) of the animals and the contaminant concentrations must be low.

Many studies have investigated the response of animals to different climatic environments in well-controlled climate chambers. Exposing pigs to different levels of gas or dust concentrations (Drummond et al., 1980; Wathes et al., 2002; Wathes et al., 2004) or to different constant or fluctuating thermal environments (Hessing and Tielen, 1994; Nienaber et al., 1996; Hamilton et al., 1998) has shown to affect animal performance and health factors. From these studies it is clear that certain levels of contaminant concentrations, certain thermal environments and certain fluctuations in the AOZ climate should be avoided. A main challenge is the translation of this knowledge into a method for judging the dynamics of the climatic environment in pig rooms on a farm, where the climate differs between day and night and from hour to hour. Several stress factors can be present at a time affecting the animals' adaptability to climatic conditions. It is likely that at the beginning of the batch, i.e. just after the animals have been moved and regrouped, the thermal conditions in a pen can quickly turn too cold. This results in an accumulation of different stress factors. It is known that diarrheic piglets are extra sensitive to cold environments (Balsbaugh et al,. 1986). Though it was found by Huyn et al. (1998) that the effects of a high temperature, a high stocking density and regrouping on animal performance were similar regardless of whether they were imposed singly or in combination.

Starting point when judging the AOZ climate is the response of animals to the dynamic pattern of the AOZ climate. The numerical indicators introduced (chapter 4) of temperature and air velocity measurements are based on the duration of thermal conditions outside the TNZ and on the magnitude of the excess. For temperature it is expressed in the number of degree-hours *(°Ch*) and for kata-value in kata-value-hours (*KVh*). The degree-hour method has also been used to quantify heating or cooling requirements in pig rooms assuming a perfect mixing of air in the room (Panagakis and Axaopoulos, 2004). The aim of chapter 4 was to evaluate the thermal comfort of weaned piglets, based on measurements within the AOZ in different pens. It was found that the value of the indicators varied largely between pens, and that the number of degree hours (*°Ch*) above the TNZ ("too warm" conditions) negatively affected animal performance. Effects on animal performance were not found for "too cold" conditions, which is extensively discussed in chapter 4.
In the evaluation method some aspects were ignored, such as quick climate fluctuations (outside and within the AOZ), possible adaptation of the piglets to adverse climatic conditions, and the diurnal variation in TNZ limits. Another aspect is that the magnitude of the excess of the TNZ limit (*°C*) and the duration (*h*) in the method contribute equally to the value of the indicator (by multiplying these), while it is likely that a short-lasting major excess is relatively more harmful than a long-lasting small excess of TNZ limits. When proven relevant, such phenomenon could easily be included in a similar evaluation method, for example by taking the square of the excess, thus expressing the cumulative excess in $°C^2h$. However, the present model for evaluation is simple and robust and at the current stage suitable for technical evaluation of climate control in rooms for weaned piglets. To a certain level the results could explain differences in animal performance.
A suggested start for further development of this methodology is to conduct a survey study under field conditions, where animal performance data are collected (for fattening pigs, because these are already available) and the cumulative excess of TNZ limits is determined based on the measured room temperature (often available). This will learn how much of the variation in animal performance could be explained by a sub-optimum macroclimate. It has been indicated before that the design of a pig facility influences animal performance (Stender et al., 2003). Later, this could be refined to the microclimate, but that would require insight into the animal performance and the AOZ climate per pen.

Controlling the AOZ climate

For controlling the AOZ climate, two technical aspects of the ventilation system are of crucial importance. The first is the hardware, i.e. the design of the room, the locations of air inlets and outlets, and the equipment for ventilation, heating (capacity, location) (chapters 2, 3, 4, 5, 6) and cooling (not addressed in this study). The second is the software, i.e. the control of these installations (chapter 6).

Simple proportional controllers are able to achieve a more or less constant temperature at the conventional sensor location in a room. However, it is found that the temperature in the AOZ fluctuates and that the AOZ temperature is on a different level. As shown in chapter 6, model predictive control solves this problem as regards the temperature in the AOZ. But improved software in the control system cannot reduce temperature differences between sensor location and other locations in the room, or temperature differences between pens. This requires the hardware to be modified.

Regarding the hardware of the ventilation system in the shift of focus from macroclimate to microclimate, the first option is to strive for climate control per pen. This would need a set of actuators per pen, such as variable air inlets per pen and the actuator of the heating system per pen, while conventionally this set is available at room level. However, the extra installations and control systems entail extra costs, so it is not expected that this is a promising development. The second and more promising option, being a main idea behind this study, is to develop ventilation systems with minimal variation in the climatic conditions between pens in a room. This can only be achieved in rooms where the amount of fresh air entering each pen is more or less equal. When in those systems the climate in the AOZ of one pen is controlled properly, this will result in a good AOZ climate control in all pens.

It was found that rooms with different ventilation systems show differences in AOZ climatic conditions (chapter 2). Ground channel ventilation proved to be advantageous as it is more effective in the removal of heat and contaminants from the AOZ. This result was expected, because in general ventilation systems with an upward flow have a better air exchange efficiency than systems with a downward flow (Breum et al., 1990). It also agrees with the findings of Aarnink & Wagemans (1997), who reported that ground channel ventilation achieved a significantly lower ammonia concentration in the AOZ than porous ceiling ventilation.

Porous ceiling ventilation (chapter 2) did not produce the desired airflow pattern. The room tested had no operator walkway, which in such rooms is needed for a proper air distribution. Fresh air entering through the ceiling is then directed towards the operator walkway and flows down. Many of the rooms for weaned piglets on farms have porous ceiling ventilation. Though in this study porous ceiling ventilation was not tested in an optimum setting, it seems likely that it is less effective at removing contaminants and heat from the AOZ than ground channel ventilation, because fresh air will mix better with room air before it reaches the AOZ.

In door-ventilated rooms it was found (chapters 2, 3, 4 and 5) that the air in one pen is displaced partly by old air from another pen upstream. This resulted in temperature differences between pens of up to 7°C within one room (chapter 4). These differences are not acceptable. Regarding this aspect ground channel ventilation, and probably also porous ceiling ventilation combined with an operator walkway, are superior to door-ventilation.

Despite the advantages mentioned of ground channel ventilation, undesired temperature differences between pens of 2°C were measured, which were caused by an unequal air distribution over the pens due to the design of the ground channel (chapter 6). To achieve an optimum design of ventilation ducts, e.g. under the floor in ground channel ventilation, there needs to be a balance between airflow distribution and outlet surface that is directly related to the pressure in the systems and thus the energy used for ventilation (El Moueddeb et al., 1998). Besides this, it is necessary to prevent dust, manure or other material from accumulating in underfloor ducts.

Further considerations

The focus of this study was on the evaluation of air inlets rather than on other relevant hardware for the AOZ climate, such as air outlet location, room insulation and availability of solid floors. The location of air outlets is also important for the airflow pattern and the distribution of contaminants in a ventilated room (Zhang et al., 2001). It is known that the low positioning of air outlets near the sources of contaminants, such as the extraction of ventilation air from below the slatted floor, will lower the concentrations of contaminating gases indoor (Lavoie et al.,1997; Aarnink and Wagemans, 1997). It is also known that doing so will reduce dust concentration (Zhang et al., 2001; Wang et al., 2001). However, if the air outlets are positioned high up, the ventilation system makes use of the thermal buoyancy above the animals, thereby reducing the energy consumption for ventilation. From a practical point of view, this position is advantageous because it enables an easy maintenance of the ventilation equipment.

In this study ground channel ventilation was combined with partly solid floors, yet in many rooms for weaned piglets on farms the floor is fully slatted. The use of ground channel ventilation systems in combination with fully slatted floors has a few disadvantages: it is more expensive to construct the ground channel, and the fresh air entering the AOZ from the operator walkway increases the risk of pit ventilation, which can result in undesired effects such as extra cooling of the animals through the slats, and gasses emerging from the pit into the AOZ.

The results lead to the conclusion that an important quality feature of a ventilation system is that the AOZ climate in all pens of a room is comparable, while climate differences between pens in one room are disadvantageous. Climate zones within pens, such as reported in chapter 2, may be acceptable because to some extent animals in a pen can choose to be in a desired climate by changing the places where they lie and dung (Randall, 1980; Randall et al., 1983). Logically, larger pens with more climatic zones increase the probability of the animals finding a comfortable location within that pen (in this study the group size varied from 10 to 35 piglets per pen). But at the same time, in rooms with large pens it is more complicated to realize a proper air distribution with fresh air supplied everywhere the animals choose to lie. This is due to the difficulty of predicting where the animals will lie and the effects of these locations (as sources of heat) on air distribution.

Conclusions

The main conclusions of this thesis are:

- The climatic environment of weaned piglets may be improved substantially if the focus is on climate in the Animal Occupied Zone (AOZ, the zone between 0 and 50 cm height in the pens), instead of on the macroclimate in the pig room.
- Differences in the AOZ climate within one pen are acceptable, while differences in the AOZ climate between pens within one room are disadvantageous.
- Air temperature is the most critical climatic variable to be measured to characterize the AOZ climatic conditions. However, in research air velocity measurements are needed for the full characterization of the AOZ climate; an ultrasonic anemometer is an accurate and usable instrument for measuring this.
- To recognize "too warm" conditions in the AOZ of a door-ventilated room for weaned piglets, both air-velocity and kata-value have limited additional value compared to only AOZ temperature measurement. This is not the case for "too cold" conditions.
- A practical method is the evaluation of AOZ thermal conditions, based on duration and magnitude of excess of the limits of the Thermo Neutral Zone of the piglets.
- The cumulative excess of "too warm" thermal conditions outside the Thermo Neutral Zone in degree hours (°*Ch*) impairs the performance of weaned piglets.
- Ground channel ventilation is superior to door-ventilation and porous ceiling ventilation in providing fresh air to the AOZ. Compared to door ventilation it shows much smaller differences in AOZ air quality and AOZ temperature between pens.
- In rooms with door-ventilation it seems not possible to keep thermal conditions in all pens within the Thermo Neutral Zone.
- Modeling the AOZ climate with computational fluid dynamics is a powerful tool for the design of geometry and location of air inlets and outlets in a pig room, but needs to be calibrated with data from real farming situations.
- Using AOZ measurements for climate control is promising if rooms have minimal variation in the climatic conditions between pens.
- Model predictive control including AOZ temperature measurement strongly reduces the temperature fluctuations in the AOZ, which are linked to conventional control systems.

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Summary

Introduction

It is extremely important to keep weaned piglets in the right climatic environment for animal health, animal performance and animal welfare. Ventilation is the key process in climate control in rooms for weaned piglets. This thesis focuses on the relationship between in the 3-dimensional ventilation and the optimal climatic environment for weaned piglets, regarding the two aspects of climate: (1) thermal climate and (2) air composition. The optimal thermal climate for the pig is defined as the Thermo Neutral Zone (TNZ). Furthermore, in an optimal climatic environment, the concentrations of contaminants such as ammonia, carbon dioxide and dust should be as low as possible.

The air in a ventilated pig room is never homogeneously mixed. The airflow pattern in the room determines the 3 dimensional temperature and contaminant distribution in the room and is linked to the occurrence of climatic zones. The climatic zone of concern is the zone where the animals live: the Animal Occupied Zone (AOZ) roughly the zone between 0 and 50 cm above the floor of the pen. In this thesis the focus is on the climate in the AOZ, i.e. the microclimate. It is distinguished from the macroclimate in the room, which is the average climate of the room.

In the Netherlands three types of ventilation systems are common in rooms for weaned piglets, i.e. porous ceiling ventilation, door-ventilation and ground channel ventilation. The ability to create and maintain an optimal climate in the AOZ is probably the most important aspect of ventilation system performance. Although this factor is so important, very little is known about patterns of the climatic conditions the piglets are exposed to when housed in rooms with different ventilation systems. The objective of this research was to improve microclimate for weaned piglets by answering the questions how to measure, evaluate and control the microclimate in rooms for weaned piglets. All experiments in the study we conducted under normal farming conditions in fully operational rooms with weaned piglets.

AOZ Contaminant en heat removal effectiveness

Chapter 2 examines how AOZ temperature and CO_2 concentration depend on the ventilation system. An experiment was performed in three rooms with ground channel ventilation, porous ceiling ventilation and door-ventilation. CO_2 concentration and temperature in the AOZ were

recorded for three successive batches with piglets. System effectiveness was expressed as the contaminant removal effectiveness (CRE) for CO_2 and the heat removal effectiveness (HRE). Values of CRE or HRE higher than 1 reflect effective removal of heat and CO_2 from the AOZ; values lower than 1 the reverse.
In all rooms, the value of CRE or HRE varied in time by varying the ventilation rate. CRE was highest in the room with ground channel ventilation, varying with measurement location. CRE was 1.39 on average and HRE was 1.13 on average in the middle of the pen. CRE was higher closer to the air inlet and lower further to the back of the pen, closer to the outlet, because air renewal was based on displacement of old air by fresh air. In the room with door-ventilation, CRE was 1.20 and HRE was 0.95 at a point in the second half of the room in the back of a pen. Air passed over the operator walkway to the back of the room, and back over the pens, resulting in a decreased CRE in the pens closer to the door that acted as an air inlet. In the room with a porous ceiling, CRE values were lower. At one sampling point, CRE was 1.01 and HRE was 0.94. In the lying area of the animals in the back of the room, CRE values were lower than at a sampling point in the front of the room. In the lying area, the heat production of the animals resulted in an upward airflow, which lowered the CRE.

Measuring air velocity in the AOZ

Supplying a large amount of fresh air in the AOZ results in high values of HRE en CRE, which is a desirable feature of a ventilation system under most circumstances. However, the thermal climate should stay within TNZ limits. For a good insight in thermal environment in the AOZ, the air velocity has to be considered. Chapter 3 describes how air velocities were measured in the AOZ by an ultrasonic anemometer to investigate air velocity differences in various pens of one room, and thereby to analyse the importance of air velocity measurements.
The anemometers were protected by a wire protection cage, which resulted in a lower air velocity measurement that was corrected by a linear correction factor of 0.83. A suitable aggregation interval for time-averaged air velocity measurements in occupied pens was 300 s. The effect of animal activity on the measured air velocity was minimal, but the location of the anemometer in a pen appeared to be important. A representative location was above the

resting place of the animals above the solid floor. The presence of an anemometer in a pen resulted in some minor changes in the lying behavior of the animals.
In the experimental door-ventilated room there was an important difference (0.04 m/s) in average air velocity between pens. The maximum air velocity of 0.15 m/s advised was exceeded in 21% of the time a pen in the back of the room. In a pen closer to the door, air velocities appeared to be too high for less than 2% of the time.

Evaluating AOZ thermal conditions

Chapter 4 focuses on parameters for indicating the quality of the thermal environment piglets in a batch are exposed to. Because batch average AOZ conditions do not take into account the fluctuations of temperature and air velocity over time, two new evaluation methods were introduced. The first was based solely on the AOZ air temperature, the other was based on the kata-value (KV), which combines air velocity and air temperature and indicates the heat loss from the animal to the environment. The methods use numerical indicators, based on the duration and the magnitude of excess of AOZ thermal conditions outside the TNZ, one referring to the number of degree-hours (°Ch) and the other to the number of kata-value-hours (KVh) during a batch. In a one-year experiment (8 batches) the methods were evaluated in a door-ventilated room.
Pens closer to the air inlet had higher temperatures and lower KV than pens in the back of the room. Momentary temperature difference between pens reached up to 7°C. During the first days of most batches, pen conditions in the back of the room were “too cold”; at the end of most batches pen conditions in the middle of the room were ”too warm”. The value of the two indicators varied per pen and per batch from 0 to 319 °Ch/ 0 to 219 KVh “too cold” and from 0 to 602 °Ch/ 0 to 793 KVh “too warm”. For “too warm” conditions there was a significant ($P<0.001$) and strong correlation between the two indicators (R^2 was > 0.96), for “too cold” conditions not (R^2 was > 0.48). Therefore, measuring air velocity in addition to temperature in the AOZ for recognition of “too cold” conditions had surplus value. Excluding outliers from one extreme warm batch, the maximum value of the indicator for “too warm” was 65°Ch. This indicator significantly affected feed conversion ratio, that increased with 2.4 g/kg per °Ch and daily growth and daily feed intake, that decreased with 2.2 g/animal and 3.0 g/animal respectively per °Ch.

It is concluded that the methods presented are useful tools in the technical evaluation of climate-systems and for a more optimal climate control in the AOZ.

Simulation of AOZ climate

Computer simulations (computational fluid dynamics) can predict 3 dimensional distributions of climatic factors in ventilated rooms. In chapter 5 the simulation results of AOZ climatic conditions are compared with measurements in a door-ventilated room. The measurements of three 1-hour periods were considered to be static situations. The observed laying locations of individual pigs were used as thermal boundary conditions in the numerical simulation model. The objectives were to gain insight in the distribution of air velocity, air temperature and CO_2 concentration in the AOZ and also to find out how accurate AOZ climate can be simulated. Measured and simulated airflow direction in the AOZ did correspond, but in air velocity magnitude there were differences. Both simulations and measurements show that the height above the solid floor is of crucial importance for the local air velocity. Both measurements and simulations showed a tendency for decreasing pen temperature when the distance to the door increased, but the measured temperatures were in general higher than the simulated. Adding radiation heat transfer in the simulations might decrease the difference. The differences between measured and simulated CO_2 concentration were relatively large, this could be caused by chosen simplifications in the simulations, such as not including the feeders in the model and assuming homogeneous conditions in the air inlet.
The level of agreement between measurements and simulation shows that the numerical simulation technique has to be refined to be an efficient tool in the design of ventilation systems for pig rooms.

Controlling AOZ temperature

It is known that there can be a significant temperature difference between the position of the climate controller sensor (room temperature) and the AOZ in a pig room. In chapter 6 the need of incorporating AOZ temperature instead of room temperature in a climate control system is explored. The objectives were to evaluate a current climate control system in a practical room with ground channel ventilation by comparing AOZ and room temperature, and 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.

Conclusions

The main conclusions of this thesis are:

- The climatic environment of weaned piglets may be improved substantially if the focus is on climate in the Animal Occupied Zone (AOZ, the zone between 0 and 50 cm height in the pens), instead of on the macroclimate in the pig room.
- Differences in the AOZ climate within one pen are acceptable, while differences in the AOZ climate between pens within one room are disadvantageous.
- Air temperature is the most critical climatic variable to be measured to characterize the AOZ climatic conditions. However, in research air velocity measurements are needed for the full characterization of the AOZ climate; an ultrasonic anemometer is an accurate and usable instrument for measuring this.

- To recognize “too warm” conditions in the AOZ of a door-ventilated room for weaned piglets, both air-velocity and kata-value have limited additional value compared to only AOZ temperature measurement. This is not the case for “too cold” conditions.
- A practical method is the evaluation of AOZ thermal conditions, based on duration and magnitude of excess of the limits of the Thermo Neutral Zone of the piglets.
- The cumulative excess of “too warm” thermal conditions outside the Thermo Neutral Zone in degree hours (°Ch) impairs the performance of weaned piglets.
- Ground channel ventilation is superior to door-ventilation and porous ceiling ventilation in providing fresh air to the AOZ. Compared to door ventilation it shows much smaller differences in AOZ air quality and AOZ temperature between pens.
- In rooms with door-ventilation it seems not possible to keep thermal conditions in all pens within the Thermo Neutral Zone.
- Modeling the AOZ climate with computational fluid dynamics is a powerful tool for the design of geometry and location of air inlets and outlets in a pig room, but needs to be calibrated with data from real farming situations.
- Using AOZ measurements for climate control is promising if rooms have minimal variation in the climatic conditions between pens.
- Model predictive control including AOZ temperature measurement strongly reduces the temperature fluctuations in the AOZ, which are linked to conventional control systems.

Samenvatting

Inleiding

Voor de gezondheid, de groei en het welzijn van gespeende biggen is het van groot belang dat ze gehuisvest worden onder goede klimaatomstandigheden. Hierbij worden twee aspecten van het klimaat in acht genomen: thermisch klimaat en luchtkwaliteit. Het optimale thermische klimaat voor varkens is gedefinieerd als de Thermo Neutrale Zone (TNZ). Verder zijn in een optimaal klimaat de concentraties vervuilende stoffen in de lucht (zoals stof, ammoniak en kooldioxide) zo laag mogelijk.
Ventilatie is het belangrijkste proces om het klimaat in een varkensstal te beheersen. De lucht in de stal is nooit homogeen gemengd, het luchtstromingspatroon bepaalt de driedimensionale verdeling van temperatuur en concentraties. De belangrijkste klimaatzone is de zone waarin de dieren leven, in dit proefschrift aangeduid met microklimaat. Deze zone bevindt zich tussen de 0 en 50 cm boven de vloer in de hokken. Dit microklimaat wordt onderscheiden van het macroklimaat (gemiddeld klimaat van de totale stalruimte). Dit proefschrift gaat op de relatie tussen het luchtstromingpatroon en het optimale microklimaat voor gespeende biggen.

Een meerderheid van de stallen voor gespeende biggen in Nederland is uitgerust met plafondventilatie, deurventilatie of grondkanaalventilatie. Hoe een ventilatiesysteem presteert hangt in sterke mate af van de mate waarin er in geslaagd wordt het gewenste klimaat in de directe omgeving van de dieren te creëren. Daarom was het opvallend dat er zeer weinig bekend was over het verloop van omstandigheden in het microklimaat in relatie tot het soort ventilatiesysteem. Doel van dit onderzoek was dan ook om het microklimaat in stallen voor gespeende biggen te verbeteren door vragen te beantwoorden over het meten in het microklimaat, het evalueren van het microklimaat en het beheersen van het microklimaat voor gespeende biggen. Alle experimenten die hiervoor gedaan zijn, zijn uitgevoerd onder praktijkrelevante omstandigheden.

De ventilatie-effectiviteit voor warmte en kooldioxide

In hoofdstuk 2 wordt een experiment beschreven waarbij onderzocht is in hoeverre de temperatuur en de kooldioxide (CO_2) concentratie in het microklimaat afhangen van het ventilatiesysteem. Bij drie ventilatiesystemen (grondkanaalventilatie, plafondventilatie en

deurventilatie) is de CO_2 concentratie en de temperatuur gemeten gedurende drie opeenvolgende ronden met biggen. De ventilatie-effectiviteit is berekend uit de gemeten CO_2 concentraties en temperaturen. Effectiviteitwaarden hoger dan 1 geven aan dat de CO_2/warmte effectief uit het microklimaat werd verwijderd, waarden lager dan 1 geven het omgekeerde aan.
Bij alle ventilatiesystemen varieerde de ventilatie-effectiviteit in de tijd door variatie in het ventilatiedebiet. De ventilatie-effectiviteit voor CO_2 was het hoogste in de afdeling met grondkanaalventilatie, en hing af van de locatie in het hok. In het midden van een hok was de ventilatie-effectiviteit voor CO_2 gemiddeld 1,39 en voor warmte 1,13. Dichter bij de controlegang, die als luchtinlaat fungeerde, was de ventilatie-effectiviteit voor CO_2 hoger en achter in het hok lager. Bij deurventilatie was de ventilatie-effectiviteit in de achterste helft van de afdeling 1,20 voor CO_2 en 0,95 voor warmte. De lucht stroomde door de deur over de controlegang naar achteren, en vervolgens terug naar voren over de hokken. Hierdoor was de ventilatie-effectiviteit voor CO_2 in de voorste hokken lager. Bij plafondventilatie in een afdeling zonder controlegang was de ventilatie-effectiviteit voor CO_2 1,01 en voor warmte 0,94 op een locatie in de afdeling waar de dieren veel lagen. Deze waarden waren relatief laag door de opwaartse luchtstroom veroorzaakt door de warmteproductie van de dieren. Op een locatie waar de dieren niet lagen was de ventilatie-effectiviteit voor CO_2 hoger.

Meten van de luchtsnelheid in het microklimaat

Veel verse lucht in het microklimaat resulteert in hoge waarden voor de ventilatie-effectiviteit. Dit is in veel omstandigheden een gewenste eigenschap van een ventilatiesysteem. Echter, de thermische condities dienen wel binnen de TNZ van de dieren te blijven. Voor een goed inzicht in deze condities is naast temperatuur ook de luchtsnelheid van groot belang. In hoofdstuk 3 wordt beschreven hoe de luchtsnelheid in het microklimaat gemeten kan worden met een ultrasone anemometer. Tevens zijn verschillen in luchtsnelheid tussen hokken binnen één afdeling onderzocht en is het belang van het meten van luchtsnelheid vastgesteld.
De anemometers werden gemonteerd in gazen beschermkooien, waardoor de gemeten luchtsnelheid in de kooi 83% was ten opzichte van die rondom de kooi. Een geschikt tijdsinterval om de metingen over te middelen was 300 s. De activiteit van de dieren in het

hok had nauwelijks invloed, maar de locatie van de sensor bleek erg bepalend voor de gemeten luchtsnelheid. Een representatieve locatie voor de luchtsnelheden op de rustplek van de dieren was midden boven de dichte vloer. De beschermkooien hadden een geringe invloed op de liglocaties van de dieren. In de afdeling met deurventilatie was er een belangrijk (0,04 m/s) verschil in luchtsnelheid tussen hokken. De geadviseerde maximale luchtsnelheid voor gespeende biggen van 0,15 m/s werd in 21% van de tijd overschreden in een hok achter in de afdeling. In een ander hok dichter bij de deur was dit minder dan 2% van de tijd.

Evalueren van de thermische condities in het microklimaat

In hoofdstuk 4 worden indicatoren gepresenteerd die de kwaliteit van de thermische condities in het microklimaat gedurende een ronde met biggen weergeven. Ronden-gemiddelde waarden van bijvoorbeeld temperatuur zijn hiervoor niet geschikt, omdat hierbij te koude periodes gedurende een ronde compenseren voor te warme periodes. Van de twee nieuwe evaluatiemethoden is de eerste alleen gebaseerd op de temperatuur in het microklimaat en de tweede op kata-waarde (KW), waarin de temperatuur en luchtsnelheid gecombineerd worden. KW is een maat voor de afkoelende werking van stromende lucht. In beide methoden wordt gebruik gemaakt van numerieke indicatoren, gebaseerd op de duur en de mate van overschrijding van de TNZ-grenzen. De indicator van de eerste methode is gelijk aan de cumulatieve overschrijding van TNZ-grenzen uitgedrukt in graad-uren (°Ch), en van de tweede methode in kata-waarde-uren (KWh). Gedurende acht ronden met biggen (ongeveer een jaar) zijn er metingen uitgevoerd in een afdeling met deurventilatie om het gedrag en de betekenis van beide indicatoren te onderzoeken.
In hokken dichter bij de deur was de temperatuur hoger en KW lager. Het temperatuurverschil op eenzelfde moment tussen hokken liep op tot 7°C. Gedurende de eerste dagen van de meeste ronden waren de hokken achter in de afdeling te koud en tegen het einde waren de hokken in het midden te warm. De waarde van de indicatoren varieerde per hok en per ronde van 0 tot 319 °Ch en van 0 tot 219 KWh te koud. Voor te warme condities varieerde de indicatoren van 0 tot 602°Ch en van 0 tot 793 KWh. Beide indicatoren hadden een sterke relatie voor de weergave van te warme condities ($R^2 > 0,96$), maar minder voor te koude condities ($R^2 > 0,48$). Daaruit blijkt dat de meting van luchtsnelheid voor het signaleren van te koude condities meerwaarde had. Nadat uitbijters veroorzaakt door één extreem warme ronde

uit de dataset waren verwijderd was de maximale waarde van de indicator 65°Ch voor "te warm". Deze indicator had een significant effect op de voerconversie, die 2,4 g/kg toenam per °Ch overschrijding, de dagelijkse groei en de dagelijkse voeropname, die 2,2 g respectievelijk 3,0 g per dier afnam per °Ch.
Beide evaluatiemethoden blijken een bruikbaar hulpmiddel op te leveren om ventilatiesystemen technisch te evalueren en het microklimaat optimaler te beheersen.

Simuleren van klimaatcondities in het microklimaat

Met computermodellen (Computational Fluid Dynamics) kan de driedimensionale verdeling van het klimaat in een geventileerde ruimte gesimuleerd worden. In hoofdstuk 5 worden simulaties en metingen beschreven van de klimaatverdeling in een afdeling met deurventilatie. Het doel was enerzijds inzicht krijgen in de verdeling van luchtsnelheid, luchttemperatuur en CO_2 concentratie in het microklimaat en anderzijds nagaan hoe nauwkeurig simulatiemodellen het microklimaat kunnen voorspellen.
De metingen en de simulaties hadden betrekking op drie periodes van elk 1 uur, waarbij de situatie binnen dat uur beschouwd is als een statische situatie. De geobserveerde liglocaties van individuele dieren zijn als thermische randvoorwaarden in de simulatie gebruikt.
De gemeten en gesimuleerde luchtstromingsrichting in het microklimaat waren vergelijkbaar, maar de grootte van de luchtsnelheid verschilde. Zowel de metingen als de simulaties lieten zien dat de hoogte boven de dichte vloer van cruciaal belang is voor de gemeten luchtsnelheid. Ook toonden ze dat de temperatuur in de hokken verder van de deur steeds lager werden, de gemeten temperaturen waren echter hoger dan de gesimuleerde. Toevoegen van warmteoverdracht tussen oppervlakken via straling in het simulatiemodel kan de verschillen mogelijk verkleinen. De verschillen tussen de gemeten en gesimuleerde CO_2 concentratie waren relatief groot, wat mogelijk veroorzaakt werd door vereenvoudigingen in het simulatiemodel. Zo waren de voerbakken als obstakels voor de luchtstroom in het hok niet meegenomen in de simulatie en werd de lucht in de deuropening homogeen verondersteld.
De mate waarin de simulatieresultaten overeenkomen met de meetresultaten laten zien dat de simulatiemodellen verfijnd moeten worden voor ze gebruikt kunnen worden bij het ontwerpen van ventilatiesystemen voor varkensstallen.

Beheersen van de temperatuur in het microklimaat

Tussen de voeler van de klimaatcomputer (macroklimaat) en het microklimaat kan er een behoorlijk temperatuurverschil voorkomen. Daarom is in hoofdstuk 6 onderzocht of het nuttig is de temperatuur in het microklimaat te gebruiken voor de klimaatregeling. In een afdeling met grondkanaalventilatie met conventionele klimaatbeheersing is de temperatuur in het microklimaat en in het macroklimaat gedurende twee ronden gemeten, en is tevens nagegaan of een model gebaseerde regelaar op basis van een microklimaatmeting voordelen biedt voor de sturing van de verwarming.
De microklimaattemperatuur was gedurende de eerste 10 dagen van beide ronden lager dan de macroklimaattemperatuur en bovendien fluctueerde deze veel meer. Deze fluctuaties werden hoogstwaarschijnlijk veroorzaakt door het aan- en uitgaan van de verwarming. Verder konden dieren nabij de microklimaatsensor de meting verstoren. Gedurende koude nachten kropen ze achter de voerbak, weg van de sensor. De gemeten temperatuur tijdens deze nachten was een goede maat voor de temperatuur van de lucht die naar de groep dieren toestroomde. Om deze reden waren deze data geschikt voor verdere analyses. Voor het voorkómen van verstorende invloed van de dieren op de meting dient de sensor in het microklimaat beter beschermd te worden.
Het verloop van de microklimaattemperatuur gedurende de vijf koude nachten bleek goed voorspelbaar te zijn met een model dat de buitentemperatuur, het ventilatiedebiet en de stand van de verwarming (aan/uit) als input heeft (R^2= 0,77). Door dit model op te nemen in een klimaatregelaar kan de verwarming in de stal aangezet worden voordat het te koud wordt en uitgezet worden voordat het te warm wordt in het microklimaat. Op die manier werd in een proef een stabielere temperatuur in het microklimaat gerealiseerd. Gedurende een periode van 11 uur nam de standaardafwijking van de temperatuur af van 0,44 tot 0,18 °C.

Conclusies

De belangrijkste conclusies van het proefschrift zijn:

- De klimaatcondities voor gespeende biggen kunnen substantieel verbeterd worden indien de nadruk wordt gelegd op het microklimaat (tussen 0 en 50 cm boven de vloer in de hokken) in plaats van op het macroklimaat in de stal.

- Verschillen in microklimaat binnen een hok zijn acceptabel, maar verschillen in microklimaat tussen hokken zijn zeer ongewenst.
- Luchttemperatuur is de belangrijkste variabele om de klimaatomstandigheden te karakteriseren. Voor een volledig beeld van het microklimaat is het echter noodzakelijk ook de luchtsnelheid te meten. Een ultrasone anemometer is hiervoor een geschikt meetinstrument.
- Om te warme omstandigheden te signaleren in het microklimaat van een afdeling met deurventilatie, hebben de katawaarde en de luchtsnelheid weinig toegevoegde waarde vergeleken met alleen een temperatuurmeting. Dit is niet het geval voor het signaleren van te koude omstandigheden.
- Het vaststellen van de cumulatieve overschrijding van de grenzen van de thermoneutrale zone van gespeende biggen is een praktische methode om het thermische klimaat te evalueren gedurende een ronde met biggen.
- De cumulatieve overschrijding van de bovengrens van de thermoneutrale zone in graaduren, heeft een aantoonbaar negatief effect op de productieresultaten van gespeende biggen.
- Bij grondkanaalventilatie komt de verse lucht beter in het microklimaat terecht dan bij deurventilatie en bij plafondventilatie. Vergeleken met deurventilatie geeft dit ventilatiesysteem veel kleinere verschillen in het microklimaat tussen hokken.
- In afdelingen met deurventilatie is het onmogelijk om de thermische condities van alle hokken binnen de thermoneutrale zone van de dieren te houden.
- Simulatiemodellen waarmee de condities in het microklimaat voorspeld kunnen worden zijn een waardevol hulpmiddel bij het ontwerp van nieuwe ventilatie- en luchtinlaatsystemen. De modellen moeten echter wel altijd gekalibreerd worden met praktijkmetingen.
- Het gebruik van microklimaatmetingen voor de klimaatregeling in stallen biedt veel perspectief als het verschil in microklimaat tussen hokken minimaal is.
- Modelgebaseerde regeling van de microklimaattemperatuur reduceert de temperatuurfluctuaties die voorkomen bij conventionele regeling.

Curriculum Vitae

Antonius Victor van Wagenberg was born on February 22nd 1974 in Vught, the Netherlands. In 1992 he completed his secondary school at the Maurick College in his village of birth and he started to study Agricultural Engineering at the Agricultural University in Wageningen. In 1997, after his internship in New Zealand, he graduated specialized in technical physics and agricultural buildings. Directly after his study he started working at the Research Institute for Pig Husbandry in Rosmalen, The Netherlands. His applied research focused on climate control in pig facilities and manure treatment. In 1999, after the Research Institute for Pig Husbandry was merged, his work continued at the Pig Division of the Research Institute for Animal Husbandry in Lelystad. There he started his pHd research on microclimate, and for this study he did measurements in the period 2000 – 2004 at the research farms of his institute in Sterksel, Raalte and Lelystad. In 2002 the institute transformed to the Applied Research Division of the Animal Sciences Group (ASG) of Wageningen University and Research Centre (WUR). End 2003 he went for 5 months as a Marie Curie Fellow to the Catholic University of Leuven, Belgium, to do a cooperative project as a part of this thesis. Currently, he is still working as a senior researcher at the Applied Research Division of ASG-WUR.