IMPLEMENTATION OF NATURAL VENTILATION IN PIG HOUSES

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Implementation of Natural Ventilation in Pig Houses

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Proefschrift

Ter verkrijging van de graad van
doctor in de landbouw- en milieuwetenschappen,
op gezag van de rector magnificus,
Dr. C.M. Karssen,
in het openbaar te verdedigen
op vrijdag 16 september 1994
des namiddags om half twee in de aula
van de Landbouwuniversiteit te Wageningen.

Cover: Proefstation voor de Varkenshouderij

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A description of experimental work and discussion on implementation of natural ventilation in pig houses is given. A literature review describes the state of the art, animal growth data are given. It includes characterization of ventilation openings, a technique to estimate the ventilation rate based on a carbon dioxide model. A control algorithm for natural ventilation in pig houses based on animal date and a dynamic model that can simulate the control algorithm are given.

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This work was compiled at the Research Institute for Pig Husbandry, P.O.Box 83, 5240AB Rosmalen, the Netherlands

Stellingen

1. Mits op de juiste wijze geïmplementeerd, leidt natuurlijke ventilatie tot een aanvaardbaar stalklimaat met lage energiekosten .
(Dit proefschrift)

2. Een discussie over de toepasbaarheid van natuurlijke of mechanische ventilatie systemen is zinloos als regeltechnische aspecten daarin niet worden betrokken.
(Dit proefschrift)

3. Het moeten naleven van de geluidsvoorschriften verbonden aan milieuvergunningen, zou varkenshouders dwingen gebruik te maken van natuurlijke ventilatie.
(Dit proefschrift)

4. Stalweer is een betere term dan stalklimaat omdat in de stal naar momentane omgevingscondities wordt gekeken en het begrip klimaat voor langjarige gemiddelden wordt gebruikt.
(G.P.A. Bot, inaugerele rede, 1994)

5. Door het ontbreken van goede kengetallen worden stalklimaatgegevens ten onrechte nog niet gebruikt in de evaluatie van de produktieresultaten in de varkenshouderij.

6. Door het eenzijdige imago van de intensieve veehouderij geven consumenten op oneigenlijke grond de voorkeur aan natuurlijke boven mechanische ventilatie.

7. De stelling van Youatt *(Youatt, 1847. The Pig. London)* dat weinig zaken meer bevorderlijk zijn voor de gezondheid en welzijn van varkens dan een ruime, goed ontworpen en goed geventileerde stal is heden ten dage nog onverminderd van kracht.

8. Bij het uitwerken van biosystemen tot bedrijfsmatige productiesystemen spelen landbouwtechnisch onderzoek en onderwijs een onmisbare rol.

9. Door de wet van de afnemende meeropbrengsten heeft landbouwkundig onderzoek in geïndustrialiseerde landen een lager rendement dan in ontwikkelingslanden, mits het menselijk leven overal gelijk gewaardeerd wordt.

10. Een hogere melkfrequentie dan tweemaal per dag verbetert het welzijn van de koe en hoeft, mits het melken automatisch gebeurt, het welzijn van de veehouder niet te schaden.

11. Bij schaalvergroting in het landbouwkundig onderzoek spelen argumenten van bezuinigingen een grotere rol dan efficiency overwegingen.

12. Het ventileren van een mening is een transportverschijnsel, waarbij naast de momentane drijvende krachten ook historische elementen in de verklaring meespelen.

C.E. van 't Klooster
Implementation of natural ventilation in pig houses
Wageningen, 16 september 1994

VOORWOORD

Dit proefschrift is voortgekomen uit onderzoek op het Proefstation voor de Varkenshouderij te Rosmalen. Binnen en buiten het Proefstation zijn veel mensen betrokken geweest bij dit onderzoek. Al deze mensen wil ik hier bedanken voor hun bijdrage.

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Mijn ouders hebben mij de mogelijkheid gegeven om te studeren, hartelijk bedankt hiervoor.

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Kees van 't Klooster

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Chapter 1

INTRODUCTION

INTRODUCTION

Problem description

In an ever more competitive world it is more than ever necessary to produce in an efficient way. In pig husbandry the focus is on better management of all production variables, including climate control. After the World War II a rapid growth of agricultural production, including pork production, was seen in Western Europe. During recent years, while having reached a saturated market for pork, current intensive production systems are critized by society with respect to animal welfare and their environmental impact. More interest arises in sustainable production systems. To decrease the negative implications of agricultural production systems on the environment, more attention is given to a balanced mineral management, reduced emissions and efficient use of energy. In climate control of pig buildings the industry has concentrated successfully on the development of mechanical ventilation systems, resulting in systems that are able to control temperature and ventilation rates automatically. The development of natural ventilation systems has received less commercial interest and so far it has resulted in systems that control temperature but lack control over ventilation rates. In breeding and nursery units, where most of the on-farm use of energy is used for heating, control of ventilation rates is important in minimizing the energy input. An option for a further reduction of energy input in pork production is the wider use of natural ventilation. The current situation regarding the application of natural ventilation in pig housing is described, including the available techniques for temperature control in natural ventilated animal housing. To achieve the full potential of efficient energy use, further development of natural ventilation systems is needed. These systems should measure and control ventilation rates and run automatically to be acceptable for pig producers.

Aim of the study

The aim of this study is to develop a technique for control of ventilation rates in natural ventilated pig houses. For implementation in climate control it is necessary to incorporate a technique to measure the ventilation rate. This study was done to explore the possibilities for implementation of natural ventilation systems in pig housing, that meet the requirements of control of the climate in the house and provide efficient use of energy. While mechanical ventilation systems have normally automatic control, this is not necessarily the case for natural ventilation systems. Pig producers who associate natural ventilation with old-fashioned manual systems with poor animal growth rates should be proviede with data on the economic benefits that can be obtained by application of natural ventilation. Data need to be collected that show that automatic control of natural ventilation can result in equal or better performance of pigs compared to pigs in current state-of-the-art mechanical ventilation systems.

Scope of the study

This study is focussed on the development of a climate control technique based on natural ventilation that can be used by Dutch pork producers. The main components of a climate control system are investigated. The hard- and software components of the system as ventilation openings, ventilation mechanisms, the measurement technique and the control algorithm of the system are studied in separation and in combination to enable technical implementation. This study does not address the issues of economics and introduction of controllers in practice. The potential application and implementation of natural ventilation systems in buildings for other species of livestock are also not a part of this study.

Strategy of the study

To provide information to producers on the potential of automatic natural ventilation, a natural ventilation system that had only automatic temperature control and no ventilation rate control will be compared to a mechanical ventilation system. After weaning, without the mother providing comfort, piglets can easily experience stress. For this category of animals it is shown in chapter 3 that at least equal results in growth can be obtained under natural ventilations systems as compared to mechanical ventilation. Crucial for a further improvement in the control of natural ventilation systems is the development of a technique to measure ventilation rates. Measurement of pressure gradients over ventilation openings have been described in chapter 4. Under static conditions it is useful to study the efficiency of ventilation openings by measuring pressure gradients as can be seen from the results presented. Influence of dynamic conditions as found in greenhouses by Bot (1983) has also been noticed in pig houses and is more difficult to measure with pressure gradients. Van 't Ooster (1993) explores whether these difficulties can be overcome under dynamic conditions in dairy housing. Dust accumulation will complicate application in pig houses. As an alternative technique already identified in chapter 2 the carbon dioxide balance is described in chapter 5 of this thesis. It is used for determination of the ventilation rates under dynamic conditions. This technique uses a carbon dioxide balance as a principle to measure the ventilation rate. The carbon dioxide production in the pig house is an important term in this balance and is associated with feed intake and heat production of pigs. An algorithm is needed to apply this measuring technique in climate control. It is based on input of animal data to the controller, rather than the climate parameters to be controlled. This algorithm is presented in chapter 6. For implementation of the algorithm to specific pig houses the controllers have to be tuned to the specifications of that particular house. A dynamic model is presented in chapter 7 as a tool that can be used for that purpose.

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Chapter 2

APPLICATION OF NATURAL VENTILATION IN INTENSIVE PIG PRODUCTION: STATE OF THE ART

C.E. van 't Klooster

Abstract
Notation

1. General aspects of natural ventilation
1.1. Labour and Energy
1.2. Health and Welfare
1.3. Animal production
1.4. Environmental implications

2. Review of physical principles of natural ventilation
2.1. Thermal buoyancy
2.2. Wind-induced effects

3. Control of natural ventilation in pig houses
3.1. Temperature control
3.2. Air flow control
3.2.1. Buoyancy and wind effects
3.2.2. Gas balances
3.2.3. Flow measurement

4. Conclusions

References

APPLICATION OF NATURAL VENTILATION IN INTENSIVE PIG PRODUCTION: STATE OF THE ART

C.E. van 't Klooster

Abstract

The potential benefits of natural ventilation are lower energy costs and less noise. Production and health status of pigs in buildings is not necessarely higher or lower in natural ventilated buildings. Reduction of the energy use for ventilation in pig houses would mean less contribution to production of greenhouse gases and associated global warming.

Automatic control of room temperature is already available for natural ventilation systems. Automatic control of airflow is not available for livestock buildings with natural ventilation, but this will be necessary to make natural ventilation acceptable to pig producers now using mechanical ventilation systems. Three principles that could be used to achieve control over air flow are discussed: Measurement of temperature and pressure gradients, measurement of gas balances and measurement of direct flow.

Notation

A_i area of inlets (m^2)
A_o area of outlets (m^2)
C_d discharge coefficient (-)
C_{gi} concentration of gas inside building (kg/m^3)
C_{go} concentration of gas outside building (kg/m^3)
c_{pe} external wind pressure coefficient (-)
c_{pi} internal wind pressure coefficient (-)
g acceleration caused by gravity (m/s^2)
G_c consumption of gas (kg/s)
G_p production of gas (kg/s)
h height within building (m)
$\bar{h}$ neutral plane (m)
T_i temperature in house (K)
T_a ambient temperature (K)
V volume of building (m^3)
v_i velocity of air in inlet (m/s)
v_o velocity of air in outlet (m/s)
v_w velocity of wind (m/s)
ΔP_h pressure difference due to thermal buoyancy at h (Pa)
ΔP_w pressure differences due to wind forces (Pa)
Ψ airflow (m^3/s)
ρ_i density of room air (kg/m^3)
ρ_a density of ambient air (kg/m^3)

1. General aspects of natural ventilation

1.1 Labour and Energy

Historically, ventilation in pig buildings started as leakage through unplanned ventilation openings or air exchange through planned ventilation openings including windows and doors. In the twentiest century an important development in ventilation systems has taken place. Ventilation in the meaning of uncontrolled exchange between room air and ambient air has developed gradually towards controlled exchange with climate control systems. Climate control systems could be defined as systems aimed to realize a desired indoor environment to a certain extent. The addition 'to a certain extent' is important since many systems are only aiming at control of temperature or ventilation rate but not the full environment including air composition and concentrations of dust particles. Air exchange through an opening is highly influenced by varying ambient conditions. This makes manual control of natural ventilation systems labour intensive and cumbersome. Pig producers are interested in automatically operated systems for ventilation. One widespread type of technology for automatic climat control in pig houses is a thermostatically controlled fan. On/off switching of fans, step wise control and control of a variable speed of fans are alternatives that are widely used in such automatic systems. Automatic ventilation systems with fans are popular. In 1982, 1985 and 1989 the percentages of piggeries with automatic operated ventilation systems in the Netherlands were 88, 86 and 89% respectively, based on Arkes et al. (1986) and Bens et al. (1991). It is noteworthy that in the period between 1982 and 1985 the percentage of automatically operated units decreased. After predicted increases in oil prices in the early 1980's, considerable numbers of pig houses with natural ventilation and manual control were erected. Energy prices never reached the expected levels and automatic control (in Dutch piggeries still associated with mechanical ventilation) has gained further in popularity. In manual control not only the amount of labour involved in control of the ventilation, estimated to be an extra 10 minutes per finishing pig place per year (Van 't Klooster et al., 1990) is disliked, but the necessity to be continuously stand-by is also resented.

The economic importance of energy prices in pig production is limited. Even in intensive pig production systems where much mechanical ventilation and heating is applied, like in the Netherlands, the on-farm costs of electricity and fuel only make 1.2% of the total production costs in the finishing phase and 3.7% in the breeding phase (fig. 1). These small percentages involve however an estimated absolute amount of US$ 47 million and US$ 68 million in annual costs of energy in finishing and breeding respectively in the Netherlands alone. Energy use for ventilation in intensive pig production in the Netherlands is 12 kWh per marketed pig (Leijen et al., 1993). A Danish study (Guul-Simonsen and Gudbjerg, 1992) on 41 pig farms, all with mechanical ventilation, found an average energy use for ventilation of 16 kWh per marketed pig. The lower recommended ventilation capacity and some natural ventilation explain the lower Dutch energy use. Barber et al. (1989) mention data from 29 Canadian pig producers with mechanical ventilation, where energy use for ventilation per marketed pig varied from 15 kWh to 37 kWh. Very inefficient fans and air-to air heat exchangers are given as reasons for the higher values in the Canadian study. With ventilation contributing to a considerable energy bill, conversion from mechanical to natural ventilation offers an incentive by reducing input costs in pig production. Menesses and Bruce (1987) reported an energy use for an automatic natural ventilation system of 3 kWh per finishing pig.

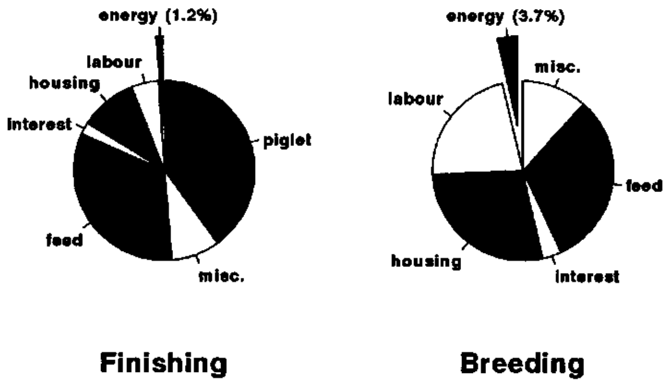

Figure 1. Distribution of costs in pig breeding and finishing units (reworked from Anon. 1993).

The savings in energy achieved by natural ventilation must be considered in connection to the cost of the ventilation control system. Van 't Klooster (1993) reported an extra investment of US$ 6.- per finishing pig place in pig houses that use a carbon dioxide sensor and natural ventilation when compared to pig houses with modern mechanical ventilation systems. These extra costs are however compensated by lower energy costs. An annual energy saving of 25.5 kWh electricity per finishing pig place is estimated (Van 't Klooster, 1993). With an electricity price of US$ 0.08 per kWh the pay-back period of the extra investment in natural ventilation systems is approximately 0.5 year.

1.2 Health and welfare

A first consideration in the health and welfare of animals and men is that no lethal concentrations of harmful constituents of room air develop. Power failure in mechanical ventilation systems can result in such situations (Harmon et al., 1990), when no back-up facilities are used in the form of an automatic electricity generator or an adequate alarm system. Natural ventilation systems ventilate independant of power, reducing the risks of complete ventilation failure.

Health of pigs can be negatively influenced by climate conditions. Although pigs can acclimate to climate conditions when conditions are steady (Verhagen, 1987), the climate is a stressor when unpredictable draught is experienced (Scheepens, 1991). Draught can be prevented in pig houses when airspeeds at animal level are under 0.15 m/s, which is in the range of natural convection currents. A ventilation system must therefore create a steady and predictable climate. In pig houses with natural ventilation the impact of wind causes large relative fluctuations in pressure gradients within the low pressure gradients in the house. This may create fluctuating and unpredictable variations in airspeed at animal level. Air distribution systems in such houses should minimize the results of these variations on the environment around the animals.

A ventilation system is a source of noise in a pig building. Natural ventilation systems produce little noise. Fans have been found to be the main source of noise (Algers et al., 1978). High noise levels may give communication problems between pigs. Algers (1988) found that piglets under high noise levels were drinking milk less frequently than piglets in farrowing rooms with lower noise levels.

Another aspect of health is air quality. Current dust levels in pig houses may harm the health of stockmen (Donham et al., 1986), but show no negative effects on growth of piglets (Van 't Klooster et al., 1993a). Phillips and Thompson (1989) found that average respirable dust levels in natural ventilated pig houses were 22% higher compared to mechanical ventilated houses (0.57 resp. 0.46 mg/m^3) and ammonia concentrations 19% lower (12.6 resp. 15.6 ppm). They do not give the degree of control over airflow, higher airflow rates may have diluted ammonia and dust, but may have had a positive influence on re-entrainment rates of dust particles as well. Robertson (1992) did not find any differences in total (4.1 resp. 3.9 mg/m^3) and settled dust (6.1 resp 7.6 g/m^2/d) nor in ammonia concentrations (8.3 resp. 8.4 ppm) in natural and mechanical ventilated pig houses. Here again, airflow may have had an influence on dust and ammonia concentrations.

Health and welfare of the pig producer are influenced by the climate on the workspot. One aspect of the climate for the producer is the thermal environment. Where the workspot is part of the air distribution system, like inlet through the feedwalk instead of baffles, the risk of high airspeeds and/or low temperatures is present. As a general rule the airspeed at the workspot should not exceed 1 m/s. As the same air inlet and air distribution systems, including baffles, ventilation ceilings and service alleys are used in both mechanical en natural ventilated pig houses, no differences in the thermal climate on the workspot are expected, provided airflows and control of airflows is the same. However control of airflow in natural ventilated pig houses has been poor so far and needs improvement to create a good thermal working conditions under all weather conditions.

The effect of noise in pig houses on the welfare of pig producers has not been investigated. Low noise levels in pig houses may facilitate better communication between persons working in a pig house and persons elsewhere on the farmyard. Pig producers may feel less confined in pig houses with natural ventilation, where ventilation openings are bigger and joint visual and voice contact with the surroundings is better.

The working conditions in terms of air quality can be improved by alternative positioning of air inlet and air outlet locations, providing the humans clean air (Van 't Klooster et al., 1993b), or by removing aerial pollutants within the building by precipitation with rapeseed oil (Takai et al., 1993).

1.3 Animal production

Olink et al. (1984a) made a comparison between two types of manual controlled natural ventilated finishing pig houses and an automatical controlled mechanical ventilated house. When houses were fully stocked, they found a higher daily gain (763 g/day vs. 744 and 745 g/day) in the mechanical ventilated house over the growing range from 25 till 112 kg live weight. Temperature reached less extreme values in the mechanical ventilated house. In a similar comparison with a third type of manual controlled natural ventilated finishing pig house a higher gain was also found in an automatical controlled mechanical ventilated house (723 vs 688 g/day), but this was accompanied by a slightly lower carcass classification (Olink et al., 1984b). In an economical evaluation of both experiments the lower construction- and energy costs outweighted the lower animal performance under natural ventilation. Milanuk et al. (1989) compared the performance of weaned piglets in an open-front building with natural ventilation and in a mechanical ventilated room. They found equal feed intake and feed conversion ratio. Climate differences within pens were bigger in the open front building. Consequently piglets utilized the available hovers better but also fouled more floorsurface (33 vs. 25%) in the open front building. In a study over 124 finishing pig farms, Geers et al.(1984) detected no differences in performances between natural and mechanical ventilation, but heating systems showed a significant improvement in production.

1.4 Environmental implications

Energy for natural ventilation is only used for adjustments in the ventilation openings, this is a neglectable part of the amount of energy required to run fans. Therefore natural ventilation contributes less to carbondioxide production and the atmospheric greenhouse effect. Pig barns also release ammonia, contributing to acid deposition and eutrophication of the environment. Where pig production is concentrated geografically, this deposition load may exceed the natural recovery capacity of the environment. The release of ammonia from pig houses can be reduced by filtering the outgoing air with filters or wet scrubbers (Demmers, 1992; Pearson et al., 1992). Such techniques require pressure gradients that can not be generated in pig houses with natural ventilation. These techniques are expensive in terms of investment and operating costs. In areas where the amounts of emitted ammonia from pig houses have to be reduced, more integrated management practices and techniques are developed that remove manure from pig houses to covered storage tanks at frequent intervals, combining reduction of ammonia release with manure treatment systems and a better air quality inside the pig buildings (den Hartog, 1992). Under such conditions it is possible to combine an energy-friendly natural ventilation system with an environment-friendly manure handling system.

2. Review of principles of natural ventilation

In and around livestock buildings the air pressure pattern shows small local differences. Local heat production and production and consumption of gasses influence local air density. The windfield also creates variations in static and dynamic pressure and results in air density gradients. An equal pressure in the air in and around farm buildings is the most favourable situation for state variables like energy and enthalphy. As soon as pressure gradients are created, air will move in an attempt to equalize pressure. The pressure gradient over such an opening gives rise to an air flow through thie opening with average velocity $\bar{v}$ as given in Eqn. (1), with C_d being the discharge coefficient and ρ the air density. The pressure difference Δp may find its origin in thermal buoyancy, in wind-induced gradients or in the combined effects of wind and temperature differences.

$$\Delta p=\frac{1}{C_d^2}\frac{1}{2}\rho\bar{v}^2 \tag{1}$$

2.1 Thermal buoyancy

To describe the convection and thereby the pressure differences over a vertical opening in a wall, created by thermal buoyancy a neutral plane is used and defined as the height $\bar{h}$ where pressure inside and outside the building are equal (Brown and Solvason, 1962; Bruce, 1978). Above the neutral plane air will move from the warm and below the neutral plane cool air will move to the warmer side (Fig. 2), even when the neutral plane crosses the opening. The pressure difference for such conditions at a height h can then be described as in Eqn. (2).

$$P_i-P_a=g(\rho_a-\rho_i)(\bar{h}-h) \tag{2}$$

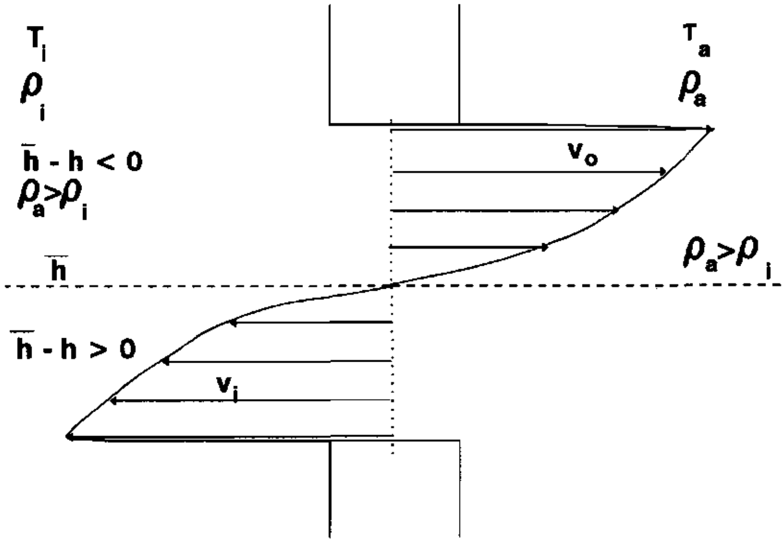

Figure 2. Natural convection flow through a ventilation opening.

In designing ventilation openings for livestock buildings with natural ventilation it is important to ensure sufficient ventilation on hot days without wind-induced ventilation, where any ventilation must originate from thermal buoyancy and hence room temperature will have to exceed ambient temperature. In a common configuration ventilation opening(s) in the side wall will function as air inlet and the ridge is the air exhaust with thermal buoyancy. The height of the individual ventilation openings is neglectible compared to the difference in elevation between inlet and outlet (Δh), as in figure 3.

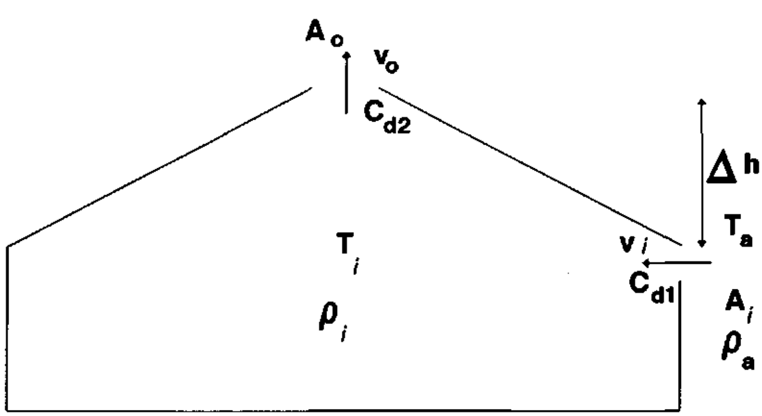

Figure 3. A pig house with two ventilation openings.

The area of ventilation openings can be related to the acceptable temperature rise in the building over ambient temperature. For the air inlet Eqn. (3) can be used. Under the assumpon of continuity of mass flow between inlet and outlet and assuming that $\rho_a/\rho_i \approx 1$, Eqn. (4) can be derived.

$$\Psi_i = A_i \overline{v_i} \tag{3}$$

$$\overline{v_o} = \frac{A_i}{A_o} \overline{v_i} \tag{4}$$

Combining Eqn. (1) and Eqn. (2) both for inlet and outlet results in Eqns (5) and (6) respectively. Adding Eqns (5) and (6) results in Eqn. (7).

$$\frac{1}{C_{di}^2} \frac{1}{2} \rho_a v_i^2 = g(\rho_a - \rho_i)(\overline{h} - h_i) \tag{5}$$

$$\frac{1}{C_{do}^2} \frac{1}{2} \rho_i v_o^2 = g(\rho_a - \rho_i)(h_o - \overline{h}) \tag{6}$$

$$\frac{1}{C_{di}^2} \frac{1}{2} \rho_a \overline{v_i}^2 + \frac{1}{C_{do}^2} \frac{1}{2} \rho_i \overline{v_o}^2 = g(h_o - h_i)(\rho_a - \rho_i) \tag{7}$$

Substitution of Eqn. (4) in Eqn. (7) results in Eqn. (8), which can be rearranged to Eqn. (9).

$$\frac{1}{C_{di}^2} \frac{1}{2} \rho_a \frac{A_i^2}{A_i^2} \overline{v_i}^2 + \frac{1}{C_{do}^2} \frac{1}{2} \rho_i \frac{A_i^2}{A_o^2} \overline{v_i}^2 = g \Delta h (\rho_a - \rho_i) \tag{8}$$

$$\overline{v_i^2} A_i^2 \left(\frac{1}{C_{di}^2 A_i^2} + \frac{1}{C_{do}^2 A_o^2} \right) = \frac{2}{\rho_a} g \Delta h (\rho_a - \rho_i) = 0 \tag{9}$$

Substitution of Eqn. (3) in Eqn. (9) results in Eqn. (10). When it is also assumed that $\Delta\rho/\rho \approx \Delta T/T$ then Eqn. (11) can be used and is often stated as a design rule for dimensioning ventilation openings.

$$\Psi_i = \frac{1}{\sqrt{\frac{1}{C_{di}^2 A_i^2} + \frac{1}{C_{do}^2 A_o^2}}} \sqrt{\frac{2g\Delta h(\rho_a - \rho_i)}{\rho_a}} \tag{10}$$

$$\Psi_i = \frac{1}{\sqrt{\frac{1}{C_{di}^2 A_i^2} + \frac{1}{C_{do}^2 A_o^2}}} \sqrt{\frac{2g\Delta h(T_i - T_a)}{T_i}} \tag{11}$$

2.2 Wind-induced ventilation

Local pressure gradients can be due to the micro-environment of a larger meteorological pressure distribution where air movement is called wind, and the resulting air exchange through an opening between a building and the environment is termed wind-induced ventilation. The static relation between wind speed (v_w) and pressure difference across a ventilation opening has been expressed by Bruce (1986) as in Eqn (12), with cpe and cpi being the outside and the inside pressure coefficient.

$$\Delta P_w = \frac{1}{2} \rho_o v_w^2 (c_{pe} - c_{pi}) \tag{12}$$

For quantitative analyses of ventilation rates it is necessary to know the values of c_{pe} and c_{pi}. The wind pressure coefficients depend on wind angle and building geometry. Choinière et al. (1992) measured the wind pressure coefficients in scale models. Shrestha et al. (1993) developed a model to find these coefficients, making it possible to calculate the ventilation rate under static conditions.

The ventilation rate caused by the dynamic wind characteristics has been studied by Bot (1983). There pressure fluctuations generate a fluctuating air flow through the opening, contributing to the energy and mass exchange between interior and exterior. In the relationship between average windspeed and ventilation rate he uses a pressure fluctuation coefficient and other opening parameters. With his measurements which include a complex relationship between opening position and presure fluctuation coefficient in greenhouses he demonstrated that the effective ventilation rate through an opening can be determined but require detailed knowledge of ventilation opening characteristics. However the resulting effective ventilation flow can be treated analogue to Eqn. 8.

3. Control of natural ventilation in pig houses

3.1 Temperature control

Natural ventilation should provide adequate heat removal also under the most severe conditions like warm summer conditions without wind. Ventilation openings in natural ventilated buildings have therefore been dimensioned in such a way that thermal buoyancy caused by the temperature rise in the building generated by the heat production in the building will provide the desired ventilation rate. The sizing of maximum ventilation opening areas for such conditions have been described (Christiaens and Debruyckere, 1977; Bruce, 1978; Timmons and Baughman, 1981; Foster and Down, 1987; Albright, 1990). Generally a temperature lift of approximately 3°C is accepted for calculating the sizes of openings. Strom and Morsing (1984) showed that room temperatures at predetermined levels can be achieved, also under warm summer conditions. Burnett and MacDonald (1987) reported that during cold weather the temperature in a pig house could be kept above the minimum desired temperature for most of the time (92 to 99%). Barrie and Smith (1986) described an unequal horizontal and vertical distribution of temperatures within the building under cold conditions with high wind speeds. The position of a temperature sensor deserves attention (Choiniere et al., 1991). With an adequate heating system installed it seems possible to control the minimum temperature. Barrie and Smith (1986) suggest further development of the natural ventilation systems to create a more uniform temperature distribution over the pens. Besides a control of dry bulb temperature only, it is also possible to control the enthalpy of the air in livestock buildings (Abschoff, 1989).

3.2 Air flow control

3.2.1 Buoyancy and wind effects

In livestock barns with natural ventilation, air will not only be removed because of the thermal buoyancy forces, but also by pressure gradients induced by wind. Therefore total ventilation rate is usually higher than the amount created by thermal buoyancy as used for calculating ventilation opening areas. Several authors have developed models to calculate the amount of ventilation as caused by the combined effect of thermal buoyancy and wind (Bruce, 1986; Brockett and Albright, 1987; Van 't Ooster and Both, 1988; Zhang et al., 1989). These models are all steady-state models. Generally the effects of wind dominate over the buoyancy effects when windspeeds are above 2 m/s (Jardinier, 1980). The input for these models require either measurement of pressure gradients over ventilation openings or information on wind speed and -direction that has to be converted into external and internal wind pressure coefficients. The possibilities for measurement of pressure gradients over ventilation openings are currently investigated (Van 't Ooster, 1993). The conversion of winddata to calculated pressure gradients over ventilation openings may be complicated by the variation in location and position of ventilation openings and by variations over time in the surrounding obstacles of the house, e.g. in the foliage of trees.

3.2.2 Gas balances

A possible objective of environmental control is to maintain a gas concentration within certain limits regardless of the ventilation rates. In those conditions a difference in concentration between ambient air and room air exists and can be used to dilute room air or to bring in oxygen. In some situations these concentration differences can also be used to derive ventilation rates from a gas balance as given in Eqn (9). Note that if this balance is applied to the room air volume, ideal mixing of this gas is assumed.

$$V\left(\frac{dC_{gi}}{dt}\right) = (G_p - G_c) - \Psi\,(C_{gi} - C_{go}) \qquad (13)$$

Ventilation rates can only be found when the sources of the concentration gradients are well known. The cause can be a consumption of the gas, as with oxygen, or a production of the gas, of witch carbon dioxyde and ammonia are examples. These gas consuming or -producing processes are part of animal husbandry or can be byproducts of activities to support the livestock operations, e.g. production of carbon dioxide by heating systems.

When measurement of ventilation rates is a goal it is also possible to inject purposely a certain amount of a particular gas in a livestock building to create a gradient in concentrations. These gases are called tracer gases and a variety of gases are used for this purpose, including SF_6, N_2O and He, with a number of variations in combining the gas release and the gas concentrations in the lapse of time (Hitchin and Wilson, 1967). When the density of the tracergas differs from the density of air, a uniform mixing of the tracergas and air may be hampered. It is a useful technique to study ventilation effectiveness in livestock buildings (Gustafsson, 1993). For continuous measurement of ventilation rates in commercial livestock buildings, tracer gas techniques have some drawbacks. The tracer gas would cause considerable expenditure for purchase and for measuring instruments and the tracer gas could form an environmental threat when large amounts would be used. A widespread use of tracer gases for this purpose is not expected and the use will be mainly confined to application as a research tool.

To determine ventilation based on gases produced or consumed in the building, it is essential to know ambient and room concentrations (gradients) and to know the production- or consumption rates. Carbon dioxide production is closely associated with feed intake of pigs (Feddes and DeShazer, 1988). The possibilities to use this knowledge to establish ventilation measurement based on a carbon dioxide balance have therefore been investigated (Van 't Klooster and Heitlager, 1994).

Ammonia is produced in pig houses mainly from the manure stored in the house. The production of ammonia is part of a series of chemical processes that elaborate prediction of the production rate at a certain moment (Anderson et al., 1987; Aarnink et al., 1992; Zhang et al., 1992). On top of that, accurate measurement of ammonia gradients between ambient and room air requires sophisticated and expensive instruments. The use of other gases being produced in the manure for estimating ventilation rates faces the same problems as ammonia and are not considered suitable for practical applications.

Water is present as a vapour. However a vapour balance is more complicated than a normal gas balance, because both evaporation and condensation have to be considered and included in the vapour balance (Keller, 1984) as important terms that are difficult to quantify. Part of the water vapour is produced by animals when latent heat is dissipated (Strom and Feenstra, 1980). Considerable amounts of water vapour are also formed by evaporation from wet surfaces on and below the floor and must be taken into account when using a water vapour balance (Huhnke et al., 1985; Clark and McQuitty, 1989). In deep litter pig houses where manure is composted this amount is even much higher than in traditional houses with anaerobic manure storage under the slats (Van 't Klooster and Greutink, 1993). Considering the complications faced when implementing a moisture balance as a means to measure ventilation, it seems that water vapour, although relatively easy and cheap to measure by sensors, is not a suitable methode to measure ventilation in commercial livestock buildings with natural ventilation.

Carbon dioxide balances offer possibilities to measure ventilation rates, but for other gases the production terms are still unsufficiently known to offer viable practical ventilation mesauring techniques.

3.2.3 Flow measurement

Direct air flow measurement by a sensor is possible in mechanical ventilated pig houses (Berckmans et al., 1991). Such an airflow rate sensor is positioned in a cylindrical section of the well defined outlet. It functions as an anemometer covering virtually the complete cross-section, thereby eliminating the need to establish the relation between position of an anemometer and airflow through such a section. Widespread application of the sensor is caused by the low price of the sensor and the high accuracy that is possible. Cylindrical sections can be applied in houses with natural ventilation as well. However then this section has to be a well defined in- or outlet. Direct air flow measurement would also be a practical method in buildings with natural ventilation, when the sensor would function equally well under those conditions. A first field test with a prototype, with bearings designed to reduce friction at low air speeds, revealed that the sensor gave constantly a useful output signal, indicating a positive air flow over 98% of the test period, while the remaining time the sensor was halted or rotating in the reverse direction (Berckmans et al., 1992). To translate this output signal to an accurate measurement of the ventilation rate in livestock buildings, a few problems still have to be solved. Under steady state conditions convective forces can create two air flows moving in opposite directions through the same horizontal opening, as Bruce (1978) showed. Under such conditions the signal of an air flow rate sensor may be useful to measure the net air flow through such an opening, but will not measure the total air exchange. This problem can be overcome by placing air flow rate sensors only in vertical cylindrical sections. Under steady state conditions wind may, alone or in combination with thermal byoyancy, create a pressure distribution pattern that makes it more complicated, as indicated in a previous section, but theoretically possible to correlate an average airspeed through an opening to an air exchange rate. In houses with natural ventilation the pressure distribution around ventilation openings is however not in a steady-state condition. The fluctuating character of wind direction and wind speed can create a highly dynamic situation in such an opening and contribute to air exchange (Bot, 1983). A comparison between air exchange as measured by a tracer gas method through the rate of decay of nitrous oxyde concentration, as described in chapter 5, and by the signal of the air flow rate sensor converted to air flow as described by Berckmans et al. (1992), assuming a low steady state pressure gradient over a vertical cylindrical section, shows little agreement between the results of both methods (Fig. 4).

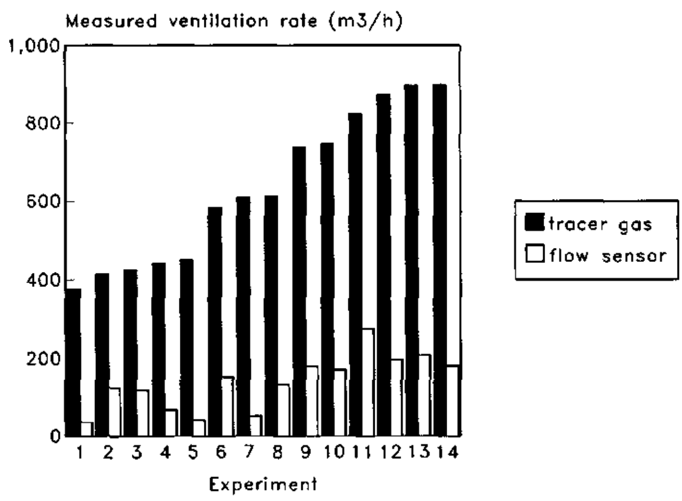

Figure 4. Comparison of a flow rate sensor with a tracer gas method in a natural ventilated pig house.

Visual observation confirmed that even in vertical cylindrical sections mounted in a roof of a pig building the airflow may move up- and downwards, influenced by wind and shows a very dynamic pattern. The airflow rate sensor does not respond to this fluctuating flow but indicates an average static flow. The fluctuating flow however contributes very effectively to the overall air exchange. In pig houses with mechanical ventilation the fan has more control over pressure gradients in the pig house, especially in the opening in which the fan is mounted. A comparison between air exchange rates in such a building, measured with an air flow rate sensor, placed in the same cylindrical section as the fan, and a tracer gas method, with constant dosing of sulphurhexafluoride, is given in figure 5 (Van 't Klooster et al., 1992).

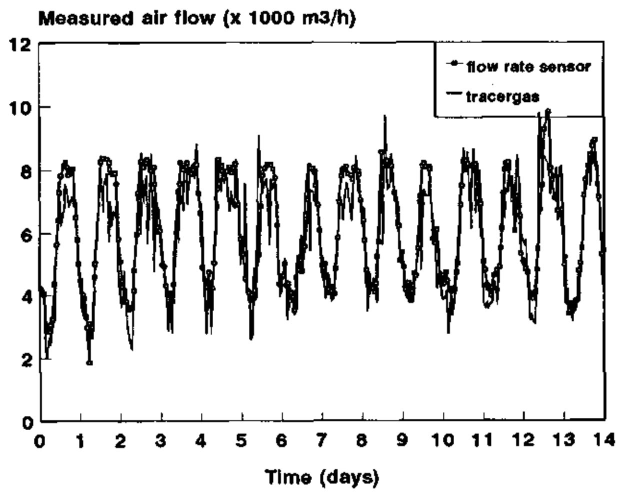

Figure 5. Comparison of a flow rate sensor with a tracer gas method in a mechanical ventilated pig house.

Although correlation between the two methods is not perfect, it is much better than in the situation with natural ventilation. Improvements in the accuracy of air flow rate sensors in natural ventilated buildings may be possible when in the section where the sensor is placed a more stable pressure gradient can be created. The total pressure caused by thermal buoyancy can be increased by either increasing the temperature difference between room and ambient air or by extra elevation difference between the lowest and the highest ventilation openings. With a given ambient temperature and a, because of other reasons desired, room temperature, the only practical way to increase this static pressure difference is to use high chimneys or steep slopes. A higher roof pitch or high chimneys will increase the construction costs. Bartussek (1989) has also developed a system whereby the air distribution in natural ventilated houses is through a horizontal porous ceiling. This system can be used to reduce the influence of the dynamic portion of the wind-pressure as air inlet can always be perpendicular to winddirection and above the horizontal ceiling ambient air can freely flow across the building as both walls have openings over their entire length above the ceiling. Measurements showed that the control over the minimum ventilation rate can be acceptable, a maximum value for carbondioxide concentration of 2300 ppm and a maximum air speed at animal level of 0.25 m/s are reported (Van 't Klooster and den Brok, 1992). Development is still needed for a smooth transition from a minimum ventilation rate to higher ventilation rates needed when excess heat has to be removed.

4. Conclusions

Natural ventilation systems for livestock buildings offer some potential advantages over mechanical ventilation systems in terms of failure-safety, energy consumption and noise production.

Mechanical ventilation systems have been developed to control room temperature as well as ventilation rates. Less industrial effort has been spent on natural ventilation systems, these have been developed to the stage of temperature control, but still lack control over ventilation rates.

For a stable indoor climate and to save energy in heated livestock buildings it is important to control the ventilation rates.

Theories to calculate ventilation rates in natural ventilated livestock buildings are mostly based on physical principles describing thermal buoyancy and wind-induced ventilation.

The use of gas balances is widely used for spot measurements of ventilation rates but hardly used in on-line control of ventilation rates.

Direct flow measurement in natural ventilated livestock buildings has a theoretical potential of offering a low-cost control technique, but still needs to be developed into operational systems.

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Chapter 3.

EFFECTS OF NATURAL AND MECHANICAL VENTILATION SYSTEMS ON GROWTH RATES OF WEANED PIGLETS

C.E. van 't Klooster

Introduction

Materials and Methods

Results

Conclusions

References

EFFECTS OF NATURAL AND MECHANICAL VENTILATION SYSTEMS ON GROWTH RATES OF WEANED PIGLETS

C.E. van 't Klooster[1]

Introduction

Both mechanical and natural ventilation in livestock buildings can be either manual or automatically operated. In comparisons between natural ventilation and mechanical ventilation it is often a comparison between a manually controlled natural ventilated building and an automatically controlled mechanical ventilated building (Geers et al.,1984; Olink et al., 1984a; Olink et al.,1984b; Milanuk et al., 1989). It is not clear whether any differences in animal performance may be fully attributed to the difference between natural and mechanical ventilation or that manual versus automatic control plays a role as well. Here a comparison in growth rates is reported between weaned piglets housed in rooms with mechanical and natural ventilation systems. The rooms with natural ventilation had manual control of temperature in the first period and had automatic control of temperature in the second period.

Materials and methods

Data over two periods have been analysed. In the first period manual natural ventilation was used and compared with automatic mechanical ventilation. In the second period the natural ventilated rooms had been converted from manual to automatic control of temperature and compared with the rooms with mechanical ventilation. In both periods the data were collected from nursery rooms as well as in from farrowing rooms where piglets were raised after weaning. Nursery rooms and farrowing rooms with both ventilation systems were used. Nursery rooms with 6 and with 12 pens per room were used with both ventilation systems.

Animal Housing

Farrowing rooms and nursery rooms have been used in the comparison, in both types all in-all out of animals is applied.

Each farrowing room consisted of 6 pens, with the same dimensions and equipment, except for the ventilation system. Rooms measured 3.3 by 10.8 m,

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all pens laid on one side of the aisle with a width of 1.1 m. Pens were 1.8 m wide and 2.2 m deep. The farrowing crates had a diagonal disposition, with the sows facing the aisle. The floor was solid concrete for 1.0 m from the aisle, followed by 1.2 m tribar metal slats. During the post-weaning period the farrowing crate is removed from the pen. Part of the solid floor is equipped with electrical floor heating. The dry feed hopper is placed on the border between solid floor and slats. Piglets are hybrids from a rotation scheme between Dutch and Finnish Landraces and Yorkshire lines. Pigs have been allocated ad-random to the various rooms.

The nursery rooms are divided in 6 or 12 pens, 1.25 by 2.65 m each, providing space for 11 piglets per pen. The floor is partly slatted, metal slats are used. The manure pit is 0.45 m deep. Pen separations were solid along the solid floor and an open trellis-work above the slats. In case piglets foul the solid floor a covered small portion of slats against the wall can be opened. The solid floor was slightly rounded. Electrical floor heating was used. Feed and water were provided ad-libitum in hoppers and nipples located above the slatted floor. In the rooms with natural ventilation a cover above the solid floor prevents draughts of cold air from falling on the piglets.

Climate control

In the mechanical ventilated rooms air enters a service aisle through a baffle system (ILB type) at eaves height to reduce wind influence. In winter periods the baffle system will draw air from the space between the roofing sheets and the roof insulation. Air is preheated in the service aisle by thermostatically controlled radiators. A counter-weighted baffle is used to distribute air from the aisle to the room. In the room a radiator is mounted directly under the baffle to supply additional heat and to prevent a drop of unmixed cool air directly on the animals. Air is extracted from the roof through an exhaust chimney with an automatic controlled valve leading to a central collection system that draws air from three or four rooms.

In the rooms with natural ventilation air inlet is through two adjustable openings at ground level located in both sidewalls allowing air to flow through the feedwalk. An adjustable open ridge serves as an air outlet. In the nursery rooms an extra provision against cold air drafts is created by means of a cover over the lying area. When the rooms are not manually operated, all ventilation openings as well as the cover over the lying area have thermostatic control over the position of the opening.

Data collection and analysis

Individual weights at the start and the end of the growing period were collected and the growing period. Performance data have been collected in ten weaner rooms with partly slatted floors, that were identical except for the ventilation system, where six rooms have automatic mechanical ventilation and five have natural ventilation. The same data have been collected from the post-weaning period in 21 farrowing rooms, where piglets remained after weaning. These farrowing rooms were completely identical except that fourteen rooms have automatic mechanical ventilation and seven have natural ventilation.

Differences in growth rates have been analyzed, taking a batch of piglets with the same starting date under the all in-all out management in a room as one experimental unit. Initial weight is taken as a covariable, allowing for corrections in differences in initial weight. Data were analyzed with ventilation system, pen numbers and farrowing/weaning house as experimental factors for variance using the Genstat package (Genstat, 1987). In the comparison with manual controlled natural ventilation a total of 191 batches were analyzed, in the comparison with the automatic natural ventilation a total of 94 batches were analyzed.

Results

The effects of ventilation system and accomodation type have been summarized in tables 1 and 2. The overall results in table 2 are poorer than the results in table 1 because in 1992 the outbreak of the PRRS disease in 1991 had still negative effects. As is already known from other sources (Peerlings and Huyben, 1985; Pfeiffer et al., 1988) leaving the piglets in the farrowing room has a significant impact on performance as is confirmed in tables 1 and 2. The transition from manual to automatic temperature control in the accommodation with natural ventilation improved growth rate from slightly lower to slightly higher compared to the automatic mechanical ventilation systems, but differences were not statistically significant. The overall daily gains in table 1 are 411.3 g/day and 417.6 g/day for the natural respectively mechanical ventilated rooms with a standard error of means (s.e.m.) of 4.9 g/day. In table 2 the overall daily are 412.1 g/day for the natural ventilated rooms and 401.9 g/day for the mechanical ventilated rooms with a s.e.m. of 8.1 g/day.

Table 1. Performance of weaned piglets between April 1988 and September 1990 in weaner rooms with partly slatted floors and in farrowing rooms, both with manually controlled natural ventilation and automatically controlled mechanical ventilation.

	weaner house		farrowing house	
	manual natural	automatic mechanical	manual natural	automatic mechanical
number of animals	6097	8221	453	943
start weight (kg)	7.4	7.4	7.8	7.3
end weight (kg)	23.1	23.2	23.4	24.5
period (days)	38.5	38.2	35.7	38.8
gain (g/day)	408[a*]	413[a]	438[b]	443[b]

[*] Different letters mean significant differences ($p<0.05$)

Table 2. Performance during 1992 of weaners in weaner rooms with partly slatted floors and in farrowing rooms, both with thermostatically controlled natural ventilation and automatically controlled mechanical ventilation.

	weaner house		farrowing house	
	automatic natural	automatic mechanical	automatic natural	automatic mechanical
number of animals	3310	3961	133	589
start weight (kg)	7.6	7.6	7.0	7.7
end weight (kg)	24.6	23.9	24.0	24.1
period (days)	41.2	41.4	38.8	38.7
gain (g/day)	411[a*]	395[a]	442[b]	437[b]

[*] Different letters mean significant differences ($p<0.05$)

When the effects of climate in a livestock building on animal performance are studied a statistical model is sometimes based on an average pen performance as experimental unit (Lopez et al.,1991a; Lopez et al., 1991b). In this model the whole group in the room is taken as experimental unit because there is only one treatment application to the whole room and pen data must therefore be considered as replicated measurements on the same experimental unit. When data would be analyzed with pen as experimental unit the effects of ventilation system would be significant. This experiment contained several rooms of each ventilation type to avoid combination of ventilation type with a particular house. Not all statistical models being used to analyse animal performance with climate as factor avoid this combination (Christenbury et al. 1987). Other publications are not clear on statistical models used to analyze animal performance in such experiments (Milanuk et al., 1989).

With manual systems humans usually set the position of the ventilation openings in the evening for the entire night, anticipating on the lowest ambient temperature (at dawn) and the highest wind speed they expect. Automatic systems can do a much better job. In the rooms with natural ventilation higher ventilation rates may have prevailed, as the houses with natural ventilation have only automatic temperature control and no airflow control. Higher ventilation rates can result in lower temperatures which generally stimulate feed intake and growth as long as temperatures do not drop below the limit where pigs can not maintain their body temperature without extra energy expenditure. In figure 1 the room temperatures are given for three identical nursery rooms all with piglets of the same age and weight, but with different control over ventilation. It can be seen that in the room with automatic control of natural ventilation maximum temperatures reach the lowest values. Fluctuations in temperatures in the room with manual control are highest.

The influence of room size within the weaning houses (6 vs. 12 pens) is illustrated in tables 3 and 4. Smaller rooms give slightly higher growth rates but the effects are not significant (s.e.m. are 5.6 and 8.9 g/day for table 1 respectively table 2). In small rooms more uniform groups of piglets will be housed with less variation in weight and age. In small (40 animals) and large (80 animals) finishing rooms Roozen and Hoofs (1992) could also not find differences in performance between these rooms.

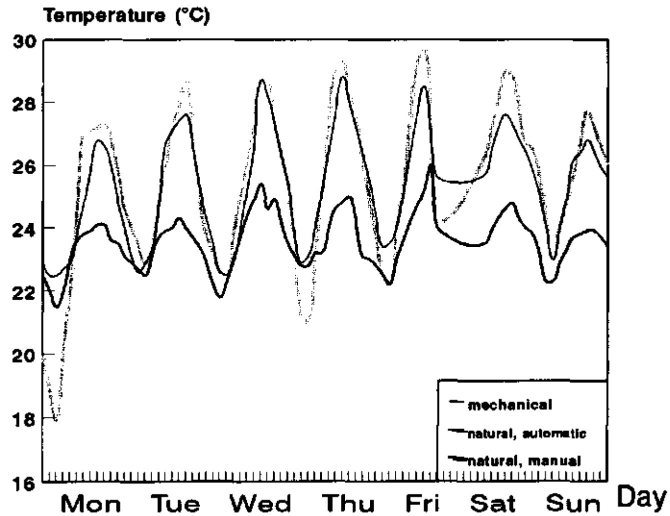

Figure 1. Room temperatures in three identical nursery rooms with equal stocking.

Table 3. Growth of weaned piglets between April 1988 and September 1990 in small and large weaner rooms.

	pens per room	
	6	12
number of animals	6583	7735
start weight (kg)	7.4	7.4
end weight (kg)	23.0	23.4
period (days)	37.7	39.3
gain (g/day)	413[a*]	407[a]

* Different letters mean significant differences ($p<0.05$)

Table 4. Growth of weaned piglets during 1992 in small and large weaner rooms.

	pens per room	
	6	12
number of animals	3247	4024
start weight (kg)	7.6	7.7
end weight (kg)	234.3	24.2
period (days)	41.2	41.4
gain (g/day)	406[a*]	396[a]

* Different letters mean significant differences ($p<0.05$)

Conclusions

In a comparison between manual controlled natural ventilation and automatically controlled mechanical ventilation no differences in growth rates of weaned piglets could be found.

In a comparison between thermostatic controlled natural ventilation and automatically controlled mechanical ventilation the piglets in thermostatic controlled natural ventilated rooms did not show significant differences in growth rates.

In a comparison between nursery rooms with 66 places and with 132 places for weaned piglets the piglets in the smaller rooms had not significant higher growth rates.

After weaning piglets raised in farrowing rooms have higher growth rates than piglets raised in nursery rooms.

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Chapter 4.

VENTILATION OPENINGS EFFICIENCY FOR PIG HOUSES WITH NATURAL VENTILATION

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Introduction

Materials and Methods

Results

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VENTILATION OPENINGS EFFICIENCY FOR PIG HOUSES WITH NATURAL VENTILATION.

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Abstract

Various configurations of ventilation openings as used in pig confinement buildings have been tested for their airflow characteristics. For a range of opening positions the pressure differences corresponding to a range of airflows were measured for each configuration. The ratio between pressure difference and kinetic energy of air-flow, based on average velocity in air inlet, the Euler number was plotted against different height/width ratios for different positions of air inlet. It was found that the Euler number not only depended on the width/height ratio of the opening as in greenhouses, but also on construction details of the openings. It was shown that streamlining the inlet increases airflow for a given pressure difference. In the tested configurations the increase was 25% in a chimney and between 0 and 35% in a wall inlet. This is also valid for conditions prevailing under natural ventilation where pressure differences vary between 0 and 10 Pa.

Keywords: ventilation openings, characteristics

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Notation

A	surface, m^2
C_d	discharge coefficient
D	(hydraulic) diameter, m
Eu	Euler number, -
H	height of opening, m
KIN_EN	volumetric kinetic energy, Nm^{-2}
ψ	airflow, m^3/s
L	length, m
Re	Reynolds Number, -
$\bar{u}$	average air velocity, m/s
W	width of opening, m
Δp	pressure difference, Pa
η	dynamic viscosity, Pa.s
ρ	air density, kg/m^3
ζ	resistance coefficient, -

Introduction

Ventilation is an important variable in the control of the inside climate conditions within an agricultural building (storage place, livestock building, green house) (King 1908; Esmay, 1969; Bruce, 1981; Van 't Ooster and Both, 1988; Albright, 1990). To allow air to enter and leave a building at least one ventilation opening is necessary. One opening is actually used in a particular housing type, the (modified) open front building. Theory has been developed to predict air exchange through one opening based on thermal buoyancy (Bruce, 1978). For open front buildings not only the size and height of the building but also the slope of the roof affects the driving thermal forces (Simango and Schulte, 1983). In calculating the ventilation rate for buildings with natural ventilation, the solar heat load must not be neglected (Van 't Ooster and Both, 1988). Performance of pigs in such houses was found to be low (Olink et al., 1984a). The geometry of ventilation openings was studied for greenhouses by Bot (1983) in scale models and De Jong (1990) in full scale buildings. Most pig buildings have more than one ventilation opening. Most mechanical ventilated pig houses have ventilation openings that are specifically intended for air inlet and distribution as well as at least one air outlet with a fan. Basic requirements of an air inlet are that it should let pass the correct amount of air and assist in a correct air distribution within the pig house, while having low investment and operating costs. The inlet baffle is the conventional air inlet system and is often found at eaves level. Theoretical attempts have been made to predict the effect inlet baffles have in providing good mixing of fresh and relatively cold air with room air. Randall and Battams (1979) have developed the application of the Archimedes number to prevent cold drafts. Good air mixing helps in controlling the air speed and air temperature at animal level (Ogilvie et al., 1990). In theory inlet baffles can therefore be controlled to assure a good climate (Albright, 1989). In practice inlet baffles performance was still susceptible to wind influence. The prevention of cold drafts in the laying area of pigs by the addition of a cover is a successful solution, but has limited appeal where added labor requirements during health checks and cleaning are not welcomed (Van 't Klooster, 1987). Indirect air inlet in combination with alternative air distribution systems have emerged like air inlet at ground level through the feed walk, reducing the risk of cold air falling on pigs (Van 't Klooster and Bluemink, 1987). Also porous ceilings have shown to improve performance of finishing pigs (Van 't Klooster and Hoofs, 1989) and are used among other countries in Austria, Germany and France with satisfying results (Bartussek, 1988; Granier et al., 1991). Other developments in air inlet systems have resulted in the use of ducts to distribute air uniformly (Barrington and Mac Kinnon, 1990) and are reported to work well under conditions with very low outside temperatures (winter 99% design temperatures below -25°C), where the severe risk of cold drafts can be reduced by combining the distribution of air with prediluting fresh air with room air.

In pig houses with natural ventilation and more than one ventilation opening the entry to and departure of air from a pig house is not necessarily confined to a particular ventilation opening. Still the demands stand for a right amount of air exchange and a good distribution of air without drafts of cold air near the pigs. Concern for sufficient air exchange during hot spells with no wind has resulted in recommendations based on thermal buoyancy of air alone for sizes and positioning of ventilation openings (Christiaens and Debruyckere, 1977). Air baffles in houses with natural ventilation also harbor the risk of air entry with insufficient mixing of fresh air and cold drafts. No efforts to overcome these risks by developing theory for necessary air conditions in the baffle have been undertaken. The problem has been overcome by either creating a cover over the laying area or by the use of alternative ventilation openings in houses with natural ventilation. The covered creep has been a successful solution in terms of providing an acceptable micro-climate for pigs (Olink et al., 1984b) but again increases labor requirements. The use of ventilation openings at ground level at both ends of the feedwalk in a pig building has also prevented cold drafts on the pigs and resulted in acceptable performance of the pigs (Olink et al., 1984b), without concessions in accessibility of pigs or increased labor requirements. Other solutions in situations where limited airflows are required, e.g. under winter conditions, have included the use of porous ceilings as an air distribution system for natural ventilation as well. (Bartussek, 1989). This system lacks the possibility to remove excess heat and has to be combined with a second system to provide an acceptable climate all year round in moderate climates. The pressure differences over ventilation openings in houses with natural ventilation are much smaller than those in houses with mechanical ventilation. The resistance to airflow within these buildings is therefore an important factor to generate sufficient airflow under all circumstances (Carpenter and Moulsley, 1978). Pearson and Owen (1994) have tested the resistance to airflow of some ventilation components. Little attention has been paid so far to the flow characteristics of air inlets at ground level and air entry through the feed walk. Snowfall may make the use of air entries at that level impractical. Airflow studies around buildings have concentrated at higher levels, roofs and chimneys (ASHRAE, 1993) and plume dispersion have received more attention than the effects on ventilation. The ventilation flow through the opening depends on the pressure difference and on the resistance of this opening. A better understanding of the geometric parameters of such openings may make a better and wider use of this system possible.

Material and methods

Ventilation openings

The flow characteristics of an inlet and an exhaust chimney as used in a pig house have been determined. The inlet system is a rectangular opening at floor level with an adjustable plywood slide-valve that opens from the bottom. Practical experiences with this type of inlet system are good in Dutch pig houses with natural ventilation. The inlet system has been measured while fully dressed, that is with rain protection (galvanized steel) and a galvanized clean wiremesh for bird protection (Fig 1). The conventional attachment of the wire-mesh results in an unnecessary constriction in the inlet that not only reduces the surface but also creates turbulences. The entrance resistance of an opening can be reduced by having curved surfaces that reduce turbulence at the entrance. In a modified opening an attachment of the same clean wire mesh was combined with flow guiders (pvc) at the outside (Fig. 2).

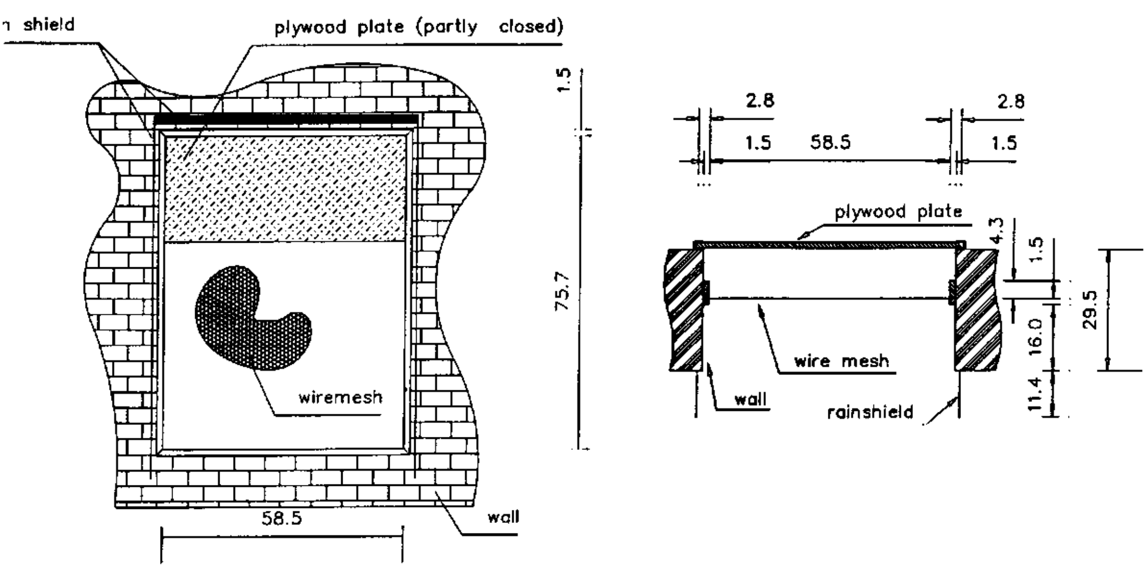

Figure 1. Front view and cross section of standard inlet.

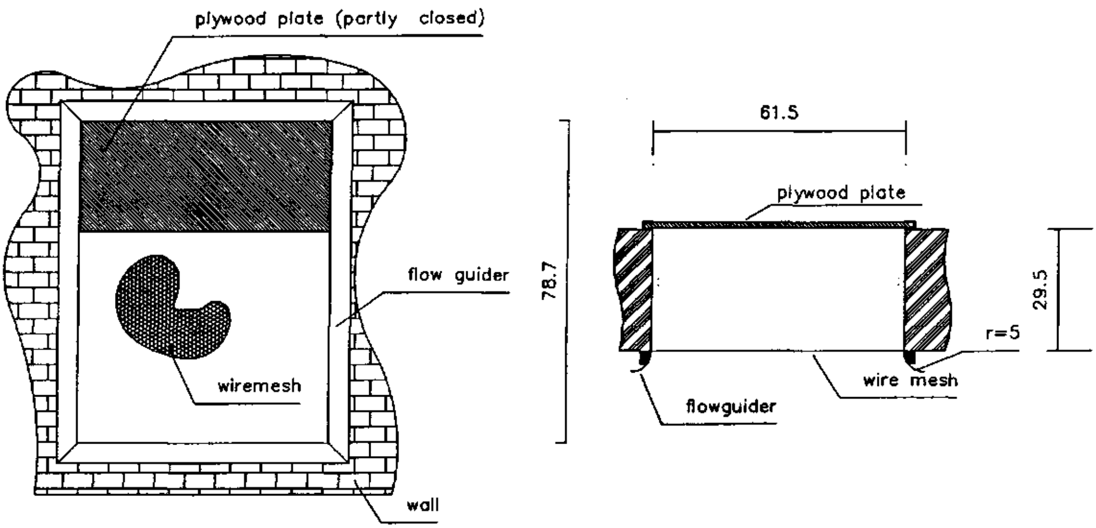

Figure 2. Front view and cross section of modified inlet.

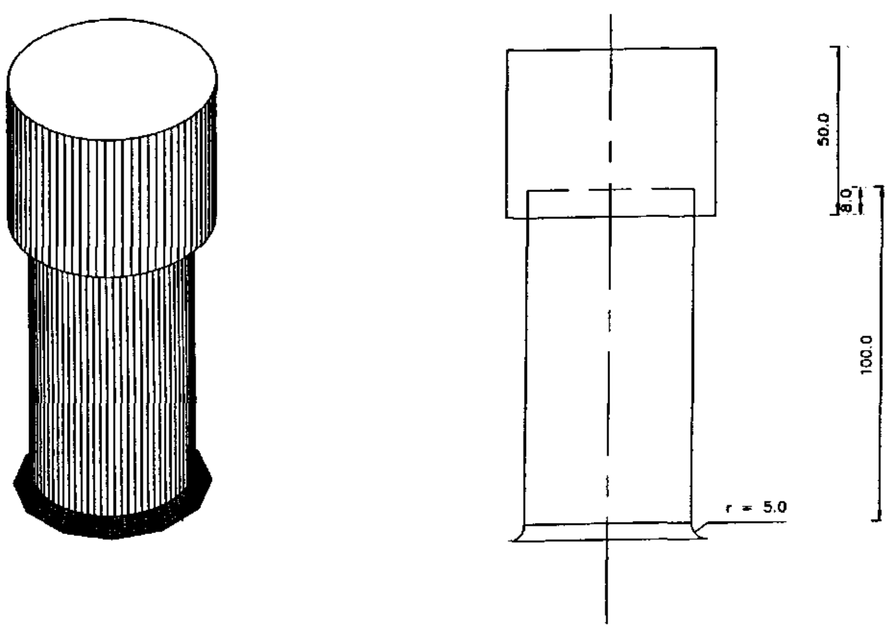

Figure 3. View and cross section of exhaust chimney with flowguider at inlet.

As a roof ventilation opening an exhaust chimney was measured. Exhaust chimneys offer the advantage over open ridge constructions that present technology to automate adjustment of the area consumes less energy. Valves in chimneys are rotated with the center of gravity on the rotation axle. Adjustable open ridges are normally controlled by vertical displacement of a plate, requiring more energy to overcome gravity. The exhaust chimney is a polyethene tube, widely used for mechanical ventilated pig houses (diameter 0.5m, length 1m). It can be equipped with a non-return valve and normally has an extra cone on top. The extra cone prevents part of any precipitation to enter the building and helps in maintaining a narrow vertical plume in order to dilute noise and odor nuisance in the vicinity of the building. The chimney is equipped with streamed air inlet and has been tested with a streamed air outlet as well (Fig. 3).

Test chamber

The ventilation openings have been mounted on top of a sealed plywood cube. Halfway in the middle of the cube a curtain has been mounted to create uniform static pressure over the cross section. The cube was airtight. In the bottom part of the cube air is brought in by a fan (ASEA A/S IP 54CL-F) that was controlled by means of a continuous variable transformer. The air flow was measured with a pulse generating air flow rate sensor. Pulses were counted by a HP-5326A timer-counter. The air flow rate sensor was calibrated in a fan test rig, conforming Dutch standard NEN 1048-II. The pressure difference (Δp) between the air before and after the ventilation opening is measured by means of a Validyne DP103-10 membrane pressure sensor. The pressure difference as used was based on the average of 30 scans at 1 second intervals of the pressure sensor signal.

Measurement procedure

For a particular setting of the ventilation opening a stable airflow was generated by the fan. The air was led through the ventilation opening and the air flow was measured by means of the air flow rate sensor and the pressure was measured. From the airflow the average velocity through the ventilation opening ($\bar{u}$) over the inlet surface (A) was determined by:

$$\bar{u} = \psi / A \tag{1}$$

The kinetic energy of the air per unit volume (KIN_EN) was calculated as:

$$KIN\_EN = \tfrac{1}{2}\, \rho\, \bar{u}^2 \tag{2}$$

The density of air, ρ, was taken at ambient temperature (20°C). The quotient between the pressure difference and the volumetric kinetic energy is called the Euler number (Eu):

$$Eu = \Delta p/(\frac{1}{2}\ \rho\ \bar{u}^2) \qquad (3)$$

Several authors use the coefficient of discharge (C_d) to express the contraction and the friction of an air flow through an opening, which relates to Eu as:

$$Eu = C_d^{-2} \qquad (4)$$

Preference is given to the use of Eu, as it gives the energy efficiency, whereas C_d gives a derivative, the air flow efficiency. Both coefficients are constant at non-viscous flow conditions. These measurements were taken three times. Subsequently another stable airflow was generated by a different setting of the voltage transformer of the fan and readings were taken again. At least six different airflows have been measured for each setting of the ventilation opening. When only inertial forces are considered and viscous forces are neglected, the air flow will only vary with density of the air and with opening geometry. A setting of the ventilation opening is expressed as a width/height ratio (W/H ratio) of the ventilation opening. At least 9 different settings have been measured for each "dressing" of the ventilation opening.

Results

Side opening

For each set of measurements on a particular dressing of the ventilation opening the data on air flow and pressure have been collected. Two example graphs are given for a fully-dressed ground level ventilation opening as used in feedwalk ventilation systems (Fig. 4).

The graph for a particular setting shows a linear and even proportional relationship in all cases (r^2>0.99). From this proportionality between Δp and $\frac{1}{2}\ \rho\ \bar{u}^2$ it is concluded that the Euler number for a particular width/height ratio is constant and does not depend on the Reynolds number. The Euler number is given as a function of the W/H ratio of different opening positions (Fig. 5). The Euler number ranges from 1.3 to 2.2. The maximum value is found for low W/H ratios and the minimum value for high W/H ratios. A second minimum is found at a W/H ratio of 1.0. For W/H ratios lower than 1.0, the width is no longer the larger dimension. If W/H ratio is defined as the largest dimension divided by the second dimension the Euler number as function of the W/H ratio has a minimum at W/H = 1.0. In "sharp" openings no minimum in the Euler number is found at a W/H value of 1.0. In this particular configuration the complex interactions between the various contractions of air flows do result in a minimum. A square opening has the lowest circumference per surface. Energetic losses due to turbulence along the wall are at a minimum and hence the pressure loss per amount of kinetic energy is relatively low. As the wall on both sides is much thicker than the top side it is expected that the sides give more resistance. As a result the Euler number will increase more rapidly as W/H deviates from 1 for the inverse of W/H being > 1.0 then for

W/H being greater than 1 (Fig. 5). The decline in Euler number at larger values of the W/H ratio can be explained by the relative reduction in turbulence by the sides and the air stream is more approaching a situation with only at the top and bottom side of the air stream turbulence.

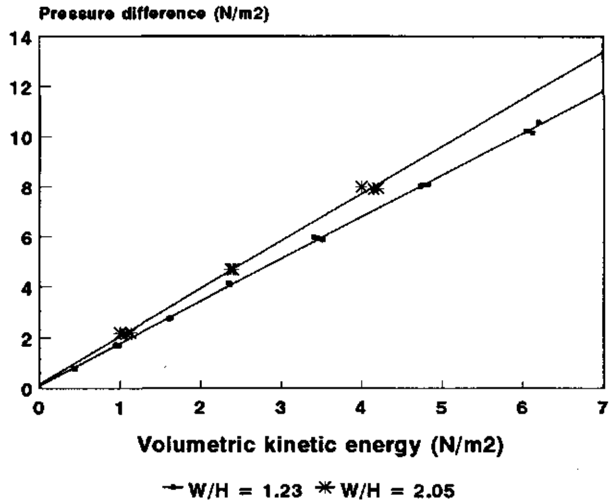

Figure 4. Pressure difference over a rectangular ventilation opening as a function of the volumetric kinetic energy in the opening for two different width/height ratios.

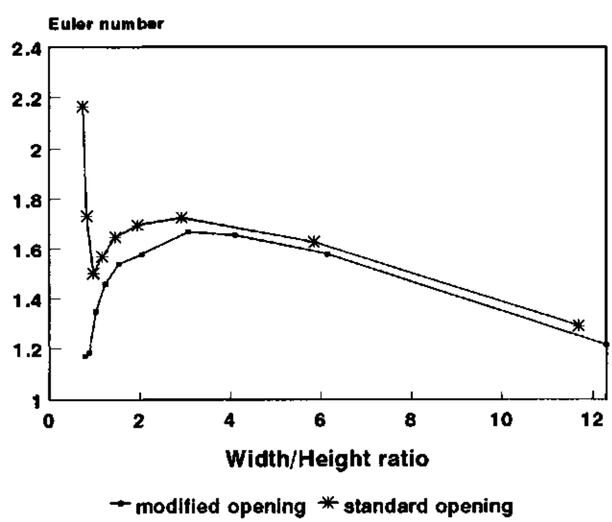

Figure 5. The Euler number as function of the width/height ratio for a standard and a modified ventilation opening.

The modified ventilation opening was tested the same way (Fig. 5). In general it is found that Euler numbers are lower for the modified opening as compared to the standard opening. The difference increases with reduction in circumference of the opening. This is in agreement with the expected reduction in turbulence. A W/H ratio below 1.0 does not give an increase in Euler numbers as with the conventional opening. Although only 2 values are available for a W/H ratio below 1.0, the tendency seems clear and the difference with the standard opening is very big and this makes this phenomenon interesting. Smoke tests with small smoke tubes revealed that a vortex in the dead space above the opening created an almost parallel air flow through the opening (Fig. 6). The vortex was much stronger in the modified opening than in the conventional opening. In the conventional opening the vortex was less strong because of various 3-dimensional disturbances of other small vortices. The modification shows that the Euler number not only depends on the W/H ratio but also on the construction of the ventilation opening. Other results reported by Bot (1983) shows the Euler number to depend on the W/H ratio only. Data by Bot were collected for sharp openings. This configuration comes much closer to a surface with negligible thickness, in which a ventilation opening is constructed. Livestock buildings however have a shell with considerable thickness due to insulation and strength requirements. As the Euler number of a ventilation opening through a wall in a livestock building is a useful way to relate airflow and resistance of the opening it is insufficient to know the W/H ratio of an opening and the Euler number has to be determined by experiment. Experimental determination of Euler numbers of ventilation openings is costly. On-site fabrication of identical ventilation openings is difficult. It is therefore suggested to use pre-fabricated standardized ventilation openings as much as possible. In this way the supplier can provide the user with the characteristics of the ventilation opening.

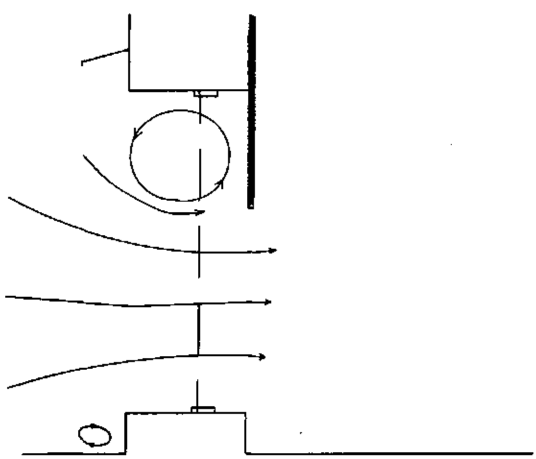

Figure 6. A vortex in a dead space of an air inlet may reduce energy losses due to turbulence.

The efficiency of ventilation openings is expressed by the Euler number. The modifications made to the ventilation opening have improved the efficiency to a considerable extent. For the modified opening the added airflow under equal pressure differences or the reduction in pressure losses under equal airflow conditions compared to the standard ventilation opening are given (Fig. 7). Gains are highest with ventilation openings fully opened. In practice this would mean when maximum ventilation is desired and when extra airflow is most welcome. In houses with natural ventilation where available pressure differences are limited and where large air flows may be required these aspects are very relevant and require more attention in designing climatic control for livestock buildings.

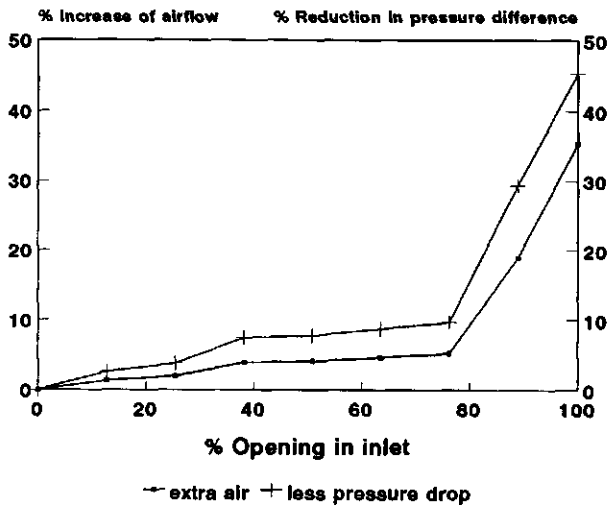

Figure 7. Effects of modifications to ventilation opening on airflow under equal pressure difference and on pressure difference under equal air flow.

<u>Chimney</u>

The measured relationship between Δp and $\frac{1}{2}\ \rho\ \bar{u}^2$ for the chimney is given (Fig. 8). A proportional relationship is found for the chimney, the chimney with outlet ring, the chimney with outlet ring and inlet flow guider and for the chimney with outlet ring and inlet and outlet flow guiders. The outlet ring reduces the resistance of the chimney. The inlet flow guider reduces the resistance very strongly and an added outlet flow guider gives a further small reduction of the resistance.

The theoretical resistance of the chimney without outlet ring can be derived as follows: For a cylindrical pipe with a smooth inner surface the pressure difference has been derived from this equation by Nikuradse for situations where the Reynolds number ($Re=u*D/\nu$) varies between 10^5 and 10^8, as is here the case. In equation (5) $\Sigma\zeta$ is the appendages part of the resistance and $(0.0032 + 0.221/Re^{0.237})$ *L/D is the pipe resistance.

$$\Delta p = (\Sigma\zeta + (0.0032 + 0.221/Re^{0.237}) *L/D) * \tfrac{1}{2} \rho \bar{u}^2 \qquad (5)$$

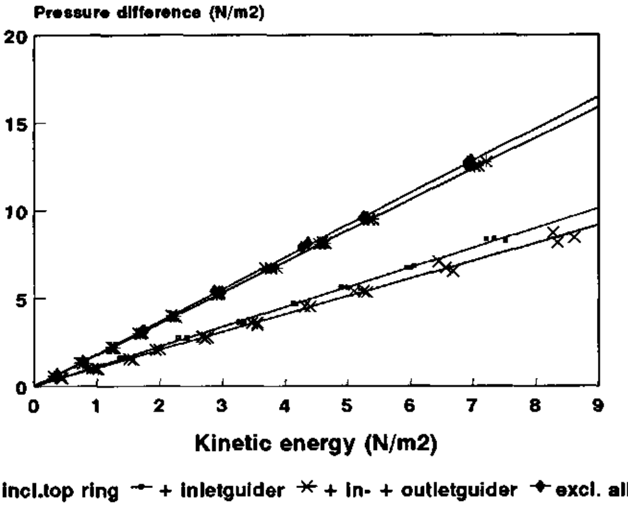

Figure 8. Pressure difference over a ventilation chimney as a function of the volumetric kinetic energy for different dressings of the chimney.

In case of an inlet flow guider the value of $\Sigma\zeta$ is available (Recknagel et al.,1990) as ζ_{in} = 0.05, $\zeta_{outlet\ ring}$ = 0.06 and ζ_{out} = 1.0. With these values, $\Sigma\zeta$ is the most important factor in the pressure drop, emphasizing the importance of air guiders. The comparison between this theoretical pressure difference and the measured pressure difference for this situation is given (Fig. 9). A good agreement between measured and calculated resistance is found. These data allow to calculate ζ_{in} for the situation without an inlet flow guider and a value of ζ_{in} = 0.8 is found to fit the measured data. The value of the outlet flow guider, ζ_{guider}, reduces the outlet resistance coefficient with 0.11. The flow guider at the entrance increases airflow with 25% under the same pressure difference. The flow guider at the top increases this flow with another 5%, making total improvement 32%.

Non-return valves in ventilation chimneys are widely used in mechanical ventilated livestock buildings with at least two chimneys, in order to reduce the entry of precipitation and cold drafts into the building in uncontrolled ways. The tested chimney has also been tested with a non-return valve (Fig. 10). From the results it shows that a pressure difference of 12 Pascal is required to open the valve and causes a significant loss in airflow. The slope of the curve with a non-return valve in Fig. 10 is smaller than the curve without this valve. As the valve is balanced with a counter weight, once the non-return valve is opened, the available area can be increased without much additional pressure and vertical kinetic energy increases quickly. Pressure gradients over 10 Pascal mean that such valves can not be used in buildings with natural ventilation.

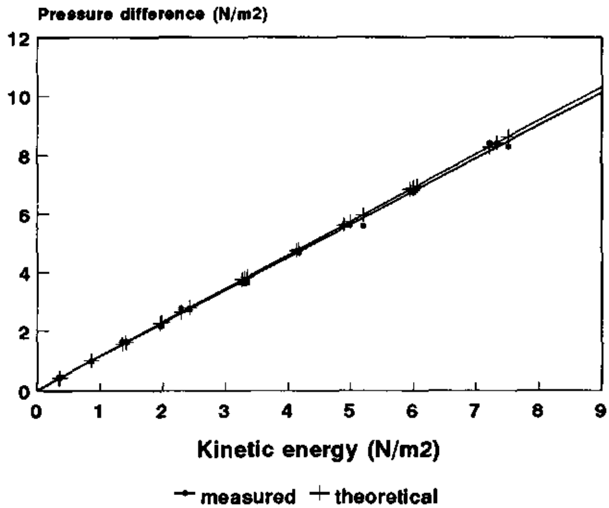

Figure 9. Measured and theoretical pressure difference as a function of the kinetic energy over a ventilation chimney with inlet flow guider.

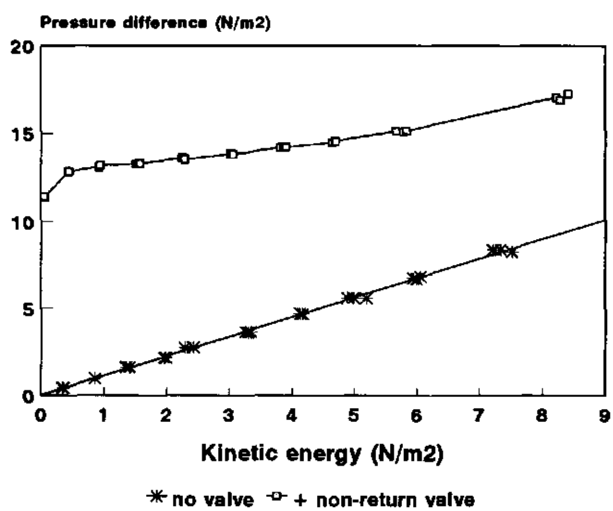

Figure 10. Pressure difference over a ventilation chimney with outlet ring and inlet flow guider as a function of the volumetric kinetic energy without and with a non-return valve.

Conclusions

The relationship between pressure difference and airflow through ventilation openings in walls, as can be expressed in the Euler number, does not only depend on the ratio between horizontal and vertical dimensions of the opening but also on the construction details.

In buildings with natural ventilation, where pressure differences are small, air flow guiders at entrances of wall openings or chimneys are able to increase maximum airflows with 35% in wall openings and with 25% in the chimney.

The resistance to airflow through circular chimneys in livestock buildings confirms theory.

It is important to optimize the resistance of ventilation openings from the point of energy use in mechanical ventilation systems and from the point of air flow capacity in natural ventilation systems.

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Chapter 5

Determination of Minimum Ventilation Rate in Pig Houses with Natural Ventilation based on Carbon Dioxide Balance

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Introduction

Carbon dioxide balance

Experimental set-up of field experiment

Results

Discussion

Conclusions

References

Based on Journal of Agricultural Engineering Research 57:279-287.

DETERMINATION OF MINIMUM VENTILATION RATE IN PIG HOUSES WITH NATURAL VENTILATION BASED ON CARBON DIOXIDE BALANCE

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Measurement of ventilation rate is necessary for good climate control in pig houses with natural ventilation and heating. A model based on a carbon dioxide balance is developed for pig houses. Included are diurnal variation patterns in carbon dioxide production. The model can estimate the ventilation rate in a pig house when carbon dioxide concentration in the pig house is measured. Measurements were made of the rates of decay in concentrations of a tracer gas in an occupied pig house with natural ventilation. The results of the tracer gas experiments and carbon dioxide model calculations showed a mean discrepancy of 13% for a natural ventilated pig building over ventilation rates between 0.1 and 0.3 kg/s. This indicates that estimating ventilation rates by using carbon dioxide measurement and applying the carbon dioxide model can be a convenient technique in climate control of pig houses with natural ventilation.

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	Notation
A	relative production rate of diurnal average carbon dioxide production
C	production rate of carbon dioxide (kg/s)
$[CO_2]$	concentration of carbon dioxide (kg/kg air)
d	days after weaning
E	metabolizable energy content of feed (kJ/kg)
F	average daily feed intake of a pig (kg/day)
G	concentration of tracer gas (kg/kg air)
k	efficiency in conversion of metabolizable energy into production
M	metabolisable energy requirement for maintenance (W)
n	number of pigs in pighouse
O	production rate of oxygen (kg/s)
Q	heat production of animals in pighouse (W)
R	respiratory quotient
S	Fraction of supplied feed that is wasted and not consumed by pigs
t	time (s)
V	Volume of room (m^3)
w	mass of average pig in pighouse (kg)
θ	mass flow (kg/s)
ρ	density of air (kg/m^3)
	Subscripts
a	ambient
c	castrated male piglets
CO2	carbon dioxide
d	daily average
e	exchange with adjacent rooms
f	female piglets
h	in pig house
i	incoming
m	momentary
N2O	tracergas
o	outgoing
T	total

1. Introduction

A minimum ventilation rate is required to maintain an acceptable air quality in pig houses. In temperate climates, buildings for young pigs require heating. Any extra ventilation above the minimum ventilation rate improves air quality but reduces room temperature or requires increased heating and thus increases costs. Therefore it is necessary to control either air quality or the minimum ventilation rate.

In pig houses with mechanical ventilation, various techniques for measuring ventilation rates are available, each with their own accuracy. Berckmans et al. (1991) showed that air-flow driven fan blades provide a low-cost solution to measure ventilation rates in pig houses. Air quality is normally not measured in pig houses with mechanical ventilation. Carbon dioxide is used as a tracer for air quality (Feddes and DeShazer, 1988). Humidity, ammonia concentrations and dust concentrations are aspects of air quality that measure only parts of the air quality problem and are expensive to measure.

Models for livestock buildings with natural ventilation have been described by Bruce (1986) and Brockett and Albright (1987) that predict ventilation rates as a function of pressure differences due to wind or thermal buoyancy. These models assume a static pressure difference over an opening. In agricultural buildings with natural ventilation, air pressure differences are small and difficult to measure accurately. Frequency and magnitude of fluctuations in pressure differences in and around agricultural buildings are high. Bot (1983) studied the fluctuating character of ventilation in greenhouses and found that this dynamic behaviour of pressure gradients in buildings with natural ventilation may contribute substantially to actual air exchange. Therefore existing models may underestimate ventilation rates.

This paper uses the carbon dioxide concentration in the pig house and animal data as a base for determining the ventilation rate in naturally ventilated pig houses. A carbon dioxide balance in a pig house is used to calculate the air exchange rate. The results of the model in terms of air exchange rate have been compared with measurements of the air exchange rate by means of nitrous oxide used as a tracer gas. Carbon dioxide is related to the metabolic rate of heat production of pigs. The molar ratio of CO_2 produced to O_2 consumed is called respiratory quotient (R) and its value depends on the material being catabolized according to Brouwer (1958). With known R values the production of carbon dioxide is calculated based on the metabolizable energy intake and weight of the pigs. The concentration in the pig house is measured and the air exchange rate is derived from the carbon dioxide production and concentration.

2. Carbon dioxide balance

Carbon dioxide is released in a pig house by respiration of pigs and production from urine and faeces of pigs. Carbon dioxide can also be part of exhaust gases of heating systems being released in the pig house. Carbon dioxide release from pig urine and faeces in stored manure is normally less than 5% of the amount produced by pigs (Schneider, 1988; Aarnink et al., 1992). Therefore the production from urine and faeces is neglected in the present model. Carbon dioxide production (C) and oxygen consumption (O) of pigs are related to the total heat production (Q_T) of pigs. Kleiber (1961) has shown that, when methane production and incomplete oxidation of nitrogen into urea are neglected, this relation can be written as:

$$Q_T = 1.155 \times 10^7\ O + 2.55 \times 10^6\ C \qquad (1)$$

To relate Q_T just to C, it is necessary and possible to substitute for O in

Eqn. (1). Carbon dioxide production is related to oxygen consumption. With R, the molar ratio between carbon dioxide production and oxygen consumption and taking into account the molecular weights of O_2 (32) and CO_2 (44) for conversion from moles to weight, Eqn. (1) can be written as:

$$Q_T = 1.155 \times 10^7 \, C \ (32/44) \, / \, R + 2.55 \times 10^6 \, C \qquad (2)$$

R is different for the production of fat, protein and carbohydrates and is influenced by the occurrence of fermentation. Feddes and DeShazer (1988) give a value of 1.0 for R for growing pigs and of 1.1 for sows with piglets. For growing pigs with R = 1.0 Eqn. (2) can be rewritten as:

$$C_d = 9.13 \ 10^{-8} \ Q_T \qquad (3)$$

Heat production per pig depends on animal weight (w) and feed intake (F) and metabolizable energy content of feed (E). To convert feed intake on a daily base to heat production in W, feed intake is divided by 86400 s/d. Heat production can be calculated as follows (Bruce and Clark, 1979):

$$Q_T = M + (1\text{-}k) \ ((FE)/86400 - M) \qquad (4)$$

According to Fowler et al. (1980), the efficiency in conversion of metabolizable energy above maintenance into production such as live weight gain or milk but not released as heat is 69%. They also found that M itself depends on weight (w) as:

$$M = 5.3 \ w^{0.75} \qquad (5)$$

The carbon dioxide production of a pig can therefore be related to the weight and the feed intake of the pig as:

$$C_d = 3.33 \times 10^{-7} \ w^{0.75} + 3.28 \times 10^{-3} \ FE \qquad (6)$$

The heat production in Eqn. (4) and the carbon dioxide production in Eqn. (6) are average daily productions. When an average daily production is used in determining ventilation rates, as has been done for humans by Penman and Rashid (1982) and for pigs by Feddes et al. (1984), diurnal variations in production are neglected. The momentary heat and carbon dioxide production have diurnal variations due to activity patterns and metabolic processes (Van der Hel et al., 1986). Ball and Bayley (1985) reported that animal activity and time of feed intake influence carbon dioxide production. When A is the relative momentary fraction of daily average carbon dioxide production, actual production can be written as:

$$C_m = A \ (3.33 \times 10^{-7} \ w^{0.75} + 3.28 \times 10^{-3} \ FE) \qquad (7)$$

The carbon dioxide balance in a pig house is made up from incoming and outgoing fluxes with the environment ($\theta_{i,CO2}$, $\theta_{o,CO2}$) an exchange flux with adjacent rooms $\theta_{e,CO2}$, a storage term based on volume (V), density (ρ) and concentration changes over time, and a production term. Assuming perfect mixing of air in the house, it can be written as:

$$V\rho \; d[CO_2]/dt = \theta_{i,CO2} + C_m + \theta_{e,CO2} - \theta_{o,CO2} \tag{8}$$

3. Pig house

3.1. *House details*

Measurements have been carried out in a room of weaned pigs (Fig. 1.).

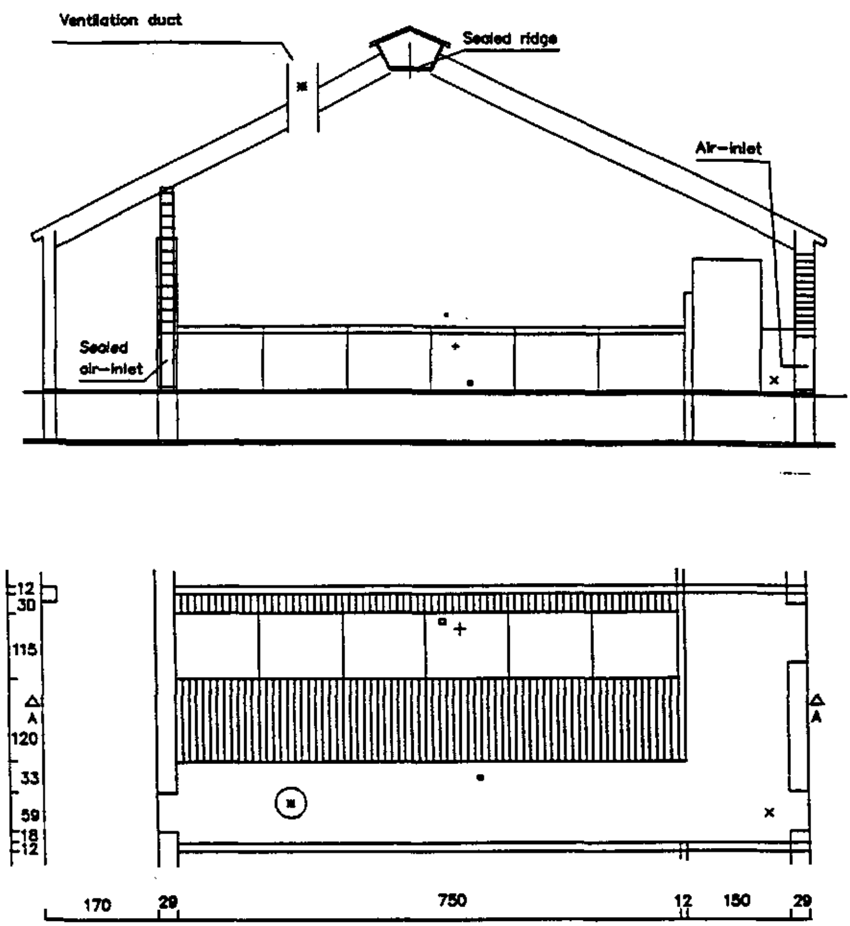

Figure 1. Plan and cross section of weaner house with natural ventilation and positions where tracer gas concentration is measured (x = near inlet, □ = above cover, + = under cover, ▪ = in feed walk, ✱ = in exhaust chimney).

Piglets enter the room with a weight of approximately 7.5 kg at an age of 4 weeks and are moved to a growing-finishing house at a weight of approximately 21 kg. The house has a ventilation opening at ground level in each sidewall and a ventilation duct in the roof. During the experiments only one of two side wall ventilation openings, as indicated in Fig. 1 was used. The solid floor in the pens is heated by electrical cables and the temperature was thermostatically controlled. The room has six pens; each pen provides space for twelve piglets. Feed is supplied ad libitum. Water is freely available through nipple drinkers. Manure is stored under the slats for periods of 6 weeks.

3.2. *Animal data*

Feed intake and weight of pigs were collected by daily registration of feed supplied at pen level and regular, mostly weekly individual weighing of piglets for four batches of piglets. When feed is available ad libitum, feed intake differs between female and castrated male piglets . Half of the pens were filled with castrated male piglets, the other half with female piglets.

3.3. *Carbon dioxide measurements*

Carbon dioxide concentrations of ambient air and room concentration were measured with an infra-red gas analyser (Horiba Priva 250E), calibrated with pure nitrogen and a calibration mixture of carbon dioxide and nitrogen before and after measurements. Carbon dioxide concentration in the pig house was measured at 1.0 m above the laying area.

4. Tracer gas measurement system

To determine the ventilation mass flow (θ), tracer gas experiments were conducted, using the rate of decay method.

Tracer gas techniques in occupied pig houses with mechanical ventilation have been reported by Leonard et al (1984). When good care was taken during measurements they found good agreement (within 5%) between rate-of-day tracer gas measurement and hot-wire anemometer measurements. Hitchin and Wilson (1967) state that N_2O, measured by infra-red analysis, is the gas that allows the widest range of useable concentrations in rate-of-decay measurements in rooms occupied by human beings. Niemelä et al. (1990) compared He, N_2O and SF_6 as tracer gases and found good agreement between the different gases under laboratory conditions except for SF_6 in stagnant air. Nederhoff et al. (1985) showed that rate-of-decay concentration measurements of injected carbon dioxide can be used to determine ventilation in commercial greenhouses.

In this experiment the air exchange rate has been estimated by using N_2O as a tracer gas in the rate-of-decay method. Tracer gas was injected in the air inlet of the pig house, which was stocked with piglets, and N_2O concentrations were kept below 100 ppm in order not to exceed short term exposure above 100 ppm (Anon, 1993). N_2O was measured with an infra-red gas analyser (URAG 2G), calibrated with pure nitrogen gas and a calibration gas before and after measurements. A multi point sampling system allowed sequential measurement with 45 s intervals at five different locations in the room. All five sampling tubes had equal lengths and were all five continuously pumped. One position was in the air inlet opening and one sample point was positioned in the air outlet. The other three locations were at various positions in the pig house as indicated in Figure 1. Tracer gas measurements were carried out in a four month period from April to July, inclusive.

The ventilation rate was determined by measuring the tracer gas concentration ($G_h(t)$) as a function of time (t) after release of gas (t=0). The slope of the logarithmic curve depends on volume of the room (V), air density (ρ) and ventilation rate. The following equation was used:

$$G_h(t=t) = G_h(t=0) \exp(-\theta\ t/(V\ \rho) \qquad (9)$$

To use Eqn. (9) further assumptions to Eqn. (8) have to be made and verified:
(1) ambient air does not contain tracer gas;
(2) there is no production of tracer gas in the room and
(3) the ventilation rate is constant during the decay measurement

5. Results

5.1 *Estimation in carbon dioxide production*

For two reasons the actual weight and feed intake on days with tracer gas experiments have not been used. Weighing the animals on days with tracer gas experiments could stress the animals and create unknown effects on heat production. Furthermore the actual weight and feed intake are necessary on a continuous base, when the carbon dioxide balance is going to be used in ventilation control.

Amounts of feed supplied have been collected at pen level. Based on collected data the feed intake of castrated male piglets (F_c) and female piglets (F_f) during the growing phase from 7.5 to 20 kg has been found as function of days after weaning (d) and fraction of feed that is supplied but wasted instead of consumed by the animals (S):

$$F_c = (1-S_c)\ (0.163-0.01166d + 0.002559d^2 - 0.0000434d^3) \qquad (10)$$

$$F_f = (1-S_f)\ (0.163-0.00795d + 0.002211d^2 - 0.0000373d^3) \qquad (11)$$

Average daily gain of piglets is affected by feed intake. Pig growth models for growing pigs have been developed by Whittemore and Fawcett (1974, 1976), Black et al. (1986), Moughan et al. (1987), Anon. (1991) and Pomar et al. (1991). These models can be used to estimate the weight of pigs as a function of time. Jacobson et al. (1989) have added a modification of a heat transfer model developed by Bruce and Clark (1979) to the Whittemore growth model to incorporate extra heat loss during cold thermogenesis (environmental temperature below thermoneutrality) and showed that this model can be used for early-weaned pigs. Daily growth rate of pigs has been calculated using data of Whittemore (1976), which separates protein and fat growth, and Eqns. (10) and (11). Feed intake of pigs is usually slightly lower than the amount of feed supplied, as these animals waste some feed. Model calculations of average daily gain and measured average daily gain from 7.5 to 21 kg body weight were similar when 4% of feed is wasted by castrated male piglets and when 3% of feed is wasted by female piglets. The same holds true for calculated and measured feed conversion ratio. These results enabled the average daily heat and average daily carbon dioxide production of pigs to be calculated for all days.

To calculate the actual carbon dioxide production at a particular moment the diurnal production pattern of carbon dioxide was measured. The diurnal distribution of carbon dioxide production by pigs, A, was measured in a similar pig house but with a constant mechanical ventilation rate. The difference between concentrations in inlet and outlet is assumed linear with the production rate, neglecting any accumulation of carbon dioxide in the room. Errors made are small when the volume of the house is low in comparison to ventilation rates and carbon dioxide production. In Figure 2 the diurnal variation in carbon dioxide production of (ad-lib fed) weaned piglets is given. This pattern was measured over 23 consecutive days with an average night length of 12 h. The distribution in carbon dioxide production is given for a different day length (10 h) but a similar time for feeding or inspection in a farrowing house (Figure 3). The daily hump in carbon dioxide production starts at the time when humans trigger animal activity by their presence. It was concluded that daylength does not play a significant role in the production pattern.

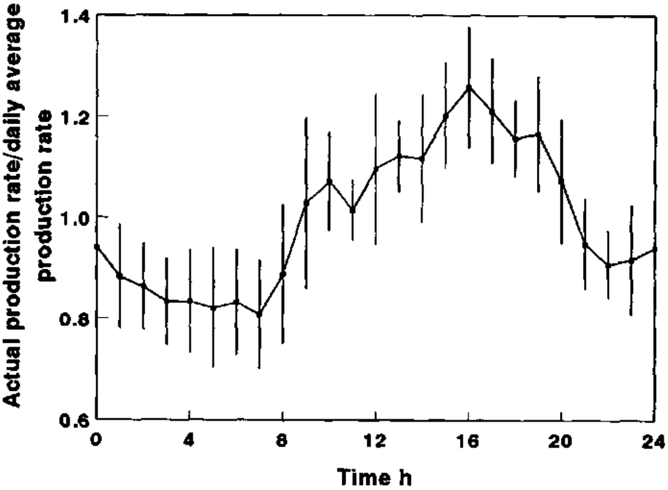

Figure 2. Diurnal pattern in carbon dioxide production of ad-lib fed weaned piglets related to average diurnal carbon dioxide production (hourly averages, error bar: + and - one standard deviation)

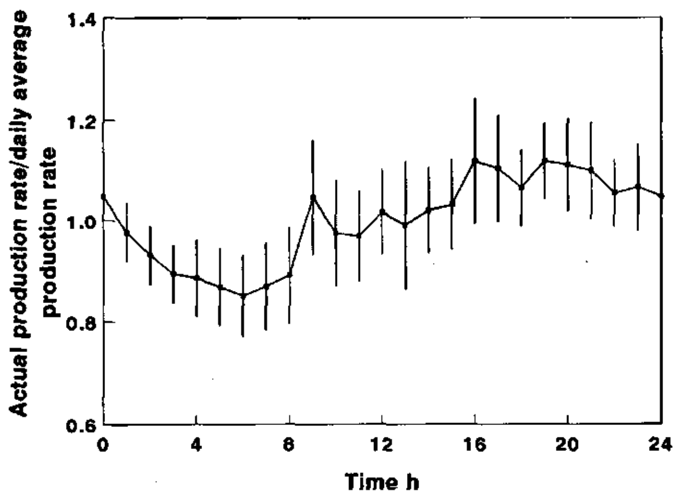

Figure 3. Diurnal pattern in carbon dioxide production in a farrowing room with six litters related to average diurnal carbon dioxide production (hourly averages, error bar: + and - one standard deviation)

5.2 *Comparison of tracer gas experiments with carbon dioxide model*

The carbon dioxide concentration was measured in a weaner room with natural ventilation and the ventilation rate was calculated, using Eqn. (8).

The ventilation rate was estimated with a tracer gas method by measuring N_2O concentrations using the rate-of-decay method and using Eqn. (9). Some assumptions as mentioned before have to be made when using this equation. These assumptions have to be checked. It assumes complete mixing of air in the room. Barber and Ogilvie (1984) found incomplete mixing of air during tracer gas experiments in isothermal conditions. To check the assumption of complete mixing in this occupied and non-isothermal room, the ventilation rates for the three positions in the room and the outlet position have been calculated. Data on decay rates at different positions in the building have been collected (Figure 4). The assumption that ventilation rates have to be constant during the decay curve means that experiments concentrate on the steady-state portion of Eqn. 8. Constant ventilation during the decay curves could not be fully realized. The concentrations of carbon dioxide during the decay curve have been used to allow elimination of data series where ventilation rates were not constant. Constantness of ventilation rate was assumed when the standard deviation in CO_2concentrations was less than 4% of the average concentration during the tracer gas experiment, leaving the dynamic portion of Eqn. 8 of limited influence on θ. Figure 5 gives these concentrations for five experiments that fulfilled this criteria. Table 1 gives physical conditions during these five experiments. Production of N_2O in pig houses can only be expected when nitrification and denitrification processes take place in stored manure, as N_2O is an intermediate product in the denitrification process (Goodroad and Keeney, 1984). Aerobic circumstances are necessary for these processes. In mixed storage of urine and faeces anaerobic conditions prevail and no N_2O production is expected. Several indicative measurements showed that no N_2O production could be detected when tracer gas experiments were not in progress.

Table 1. Average physical conditions during five experiments comparing measured ventilation rates.

	Experiment				
	1	2	3	4	5
Inside temperature (°C)	26.2	24.0	23.4	23.7	24.0
Ambient temperature (°C)	23.6	20.1	18.0	10.2	11.3
Wind speed (m/s)	5.3	1.6	0.8	4.5	6.1
Wind direction	NE	E	E	W	NW
CO_2 concentration (ppm)	1430	1820	1910	2360	2700
Ventilation rate (kg/s) by					
CO_2 balance	0.288	0.172	0.171	0.122	0.115
tracer gas	0.286	0.201	0.191	0.144	0.147

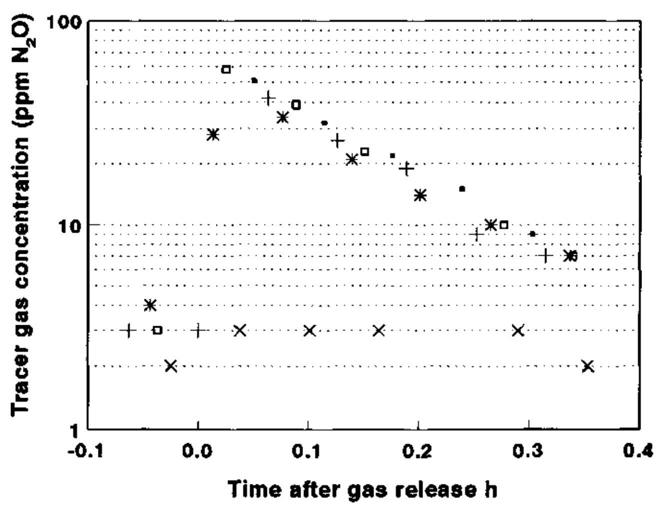

Figure 4. Spatial variation in tracer gas concentration in a pig house with pigs, using the rate-of-decay method (x = near inlet, □ = above cover, + = under cover, ▪ = in feed walk, ✱ = in exhaust chimney).

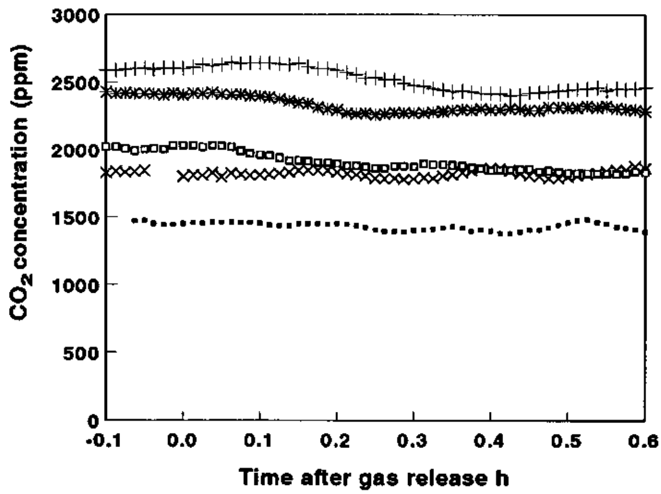

Figure 5. Variation in carbon dioxide concentrations during tracer gas experiments (■ = experiment 1; x = experiment 2; □ = experiment 3; ⊗ = experiment 4; + = experiment 5)

Leakage and air exchange of the pig house to adjacent rooms and the ambient atmosphere was measured in a seperate experiment with all ventilation openings closed (Figure 6). Total air exchange was found to be 0.02 kg/s, equal to 0.48 air changes per hour, with all ventilation openings closed.

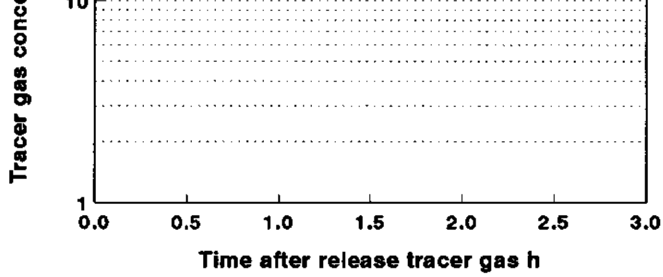

Figure 6. Rate-of-decay of tracer gas in empty room with ventilation openings closed (x = near inlet; □ = above cover; + = under cover; ⊗ = in feed walk).

Tracer gas experiments have been conducted to determine air exchange between the room with pigs and its surroundings. The carbon dioxide model has been used to calculate air exchange during the same experiments (Figure 7). Measured ventilation rates in the tracer gas experiments showed a mean difference of 13%.

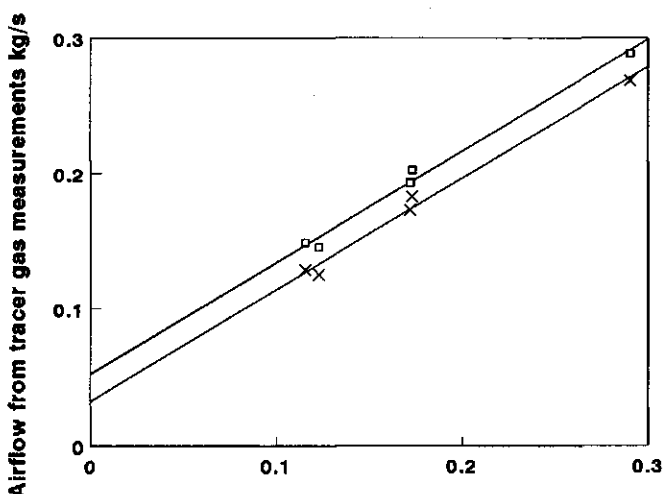

Figure 7. Ventilation rates found by tracer gas measurements and by the carbondioxide model (□ = tracergas data including air exchange with adjacent rooms, x = tracergas measurements corrected for air exchange with adjacent rooms).

6. Discussion

This paper confirms work of Leonard et al. (1984) that in occupied pig houses rate-of-decay measurements give agreement with other techniques to estimate the ventilation rate. Leonard et al. worked in pig houses with mechanical ventilation, this paper presents results for a pig house with natural ventilation. Figure 4 shows a uniform spatial distribution of tracer gas within the house. The uniform distribution is probably caused by the heat production of the animals, that creates enough thermal buoyancy within the house to prevent serious problems with stagnant air.

In the differences in results as presented in Fig. 7 experimental errors play a role. Accuracy is reduced by experimental errors in the tracer gas experiments and by errors in the carbon dioxide model. The probable experimental error in tracer gas experiments can be estimated using partial differentiation of the ventilation rate θ. According to Eqn. (9), θ can be written as

$$\theta = V\rho \,/\, t \quad \ln\left(C(0)/C(t)\right) \qquad (12)$$

$$\frac{\partial\theta}{\theta} = \sqrt{\left[\left(\frac{\partial V}{V}\right)^2 + \left(\frac{\partial\rho}{\rho}\right)^2 + \left(\frac{\partial C(0)}{C(0)^2}\right)^2 + \left(\frac{\partial C(t)}{C(t)^2}\right)^2\right]} \qquad (13)$$

With relative errors in volume, density and concentrations estimated to be 3, 1, 2 and 2% respectively this amounts to a probable error in θ of 3%. Besides these errors the assumption of complete mixing is not completely met and adds to the error. This error in θ can be estimated from the standard deviations in the mean ventilation rates derived from the four relevant measuring positions, which is 5.1%. The total probable error, as the square root of the sum of squares, will therefore be 6%.

The accuracy of the results of the model with the carbon dioxide balance is influenced by the precision of the model equations, by the measuring accurary of carbon dioxide concentration and by accuracy of animal weight and feed intake. Feed that has been wasted by pigs is not converted into carbon dioxide and an increase in feed waste by pigs, also increases the calculated ventilation rate with almost the same percentage. Model predictions of ventilation rates are therefore affected by feed losses.

In the carbon dioxide model the exchange of air with adjacent pigrooms plays only a role when concentration gradients between carbon dioxide concentrations in neighbouring rooms exist.

In a tracer gas experiment the air exchange of an empty pigroom with its environment was measured as being 0.02 kg/s (Figure 6). Physical observations showed leakage between rooms to be a major part of the total leakage of the room. Temperature in a pig room will tend to follow ambient temperature more closely in empty pig rooms than in occupied pig rooms and smaller pressure differences are generated in empty rooms. Higher temperature and pressure differences will increase leakage in pig rooms. In the empty room temperature was on average 0.8°C above ambient temperature compared to an average of 7.8°C above ambient temperature during the experiments with occupied rooms. The air exchange level through leakage was not measured in occupied pig buildings. Tracer gas experiments to measure leakage in occupied rooms with closed ventilation openings were not carried out in order not to endanger the life of the pigs by prolonged exposure to high concentrations of N_2O. If the leakage of tracer gas in a room with open and closed ventilation openings was equal and only existing with adjacent rooms, the mean difference between tracergas measurements and carbon dioxide balances would reduce from 13 to 5%, when carbon dioxide concentration in adjacent rooms was also equal. This can also be seen in Fig. 7 where ventilation between adjacent rooms is assumed as 0.02 kg/s for all experiments and subtracted from the ventilation rates measured by tracergas. It also shows that the relatively large disagreement between both methods for low ventilation rates is strongly reduced and comes within the experimental errors. This indicates that exchange between adjacent compartments in a building can indeed be a cause of differences between both methods and further research is needed to quantify these effects. Leakage in buildings with open ventilation openings could be higher than in buildings with closed ventilation openings as internal pressure differences can probably follow ambient pressure fluctuations to a greater extent. The dynamic components of ventilation have been described by Bot (1983) for ventilation openings but could play a role in leakage as well.

Feddes et al. (1984) have calculated overall mean ventilation rates with carbon dioxide concentrations in experimental facilities for twelve pigs and found a mean discrepancy of 7% in comparison with anemometer measurements. Air exchange between adjacent experimental facilities used by Feddes et al. (1983), if any, might have been much smaller than in the full-scale building used in this paper and could be an explanation why two methods showed more agreement in the experiments of Feddes et al. (1983) than in this paper. Another reason could be that Feddes et al. (1983) have not included the considerable diurnal variation in the production of carbon dioxide. Their overall mean ventilation rates can therefore not be compared with momentary data as presented in this paper. Data presented in this paper suggest that the carbon dioxide balance might result in a convenient method for on-line measurement of ventilation rates in pig houses with natural ventilation.

7. Conclusions

Diurnal variations in carbon dioxide production must be taken into account when the carbon dioxide concentration is used to estimate the ventilation rate in occupied pig houses.

Measurement of the rate-of-decay in concentration is a useful technique to determine ventilation rates in occupied pig houses with natural ventilation.

The results of the tracer gas experiments and carbon dioxide model calculations showed a mean discrepancy of 13% for a natural ventilated pig building over ventilation rates between 0.1 and 0.3 kg/s. Both methods use gasses with the same density, one in a constant flow, the other in a rate of decay technique. In the "constant" flow method the production term is the important term for the accuracy, in the rate of decay effective building volume is an important parameter.

The use of a model for carbon dioxide production in combination with continuous measurement of the carbon dioxide concentration is a promising technique for continuous estimation of the ventilation rate possible for an occupied pig house with natural ventilation.

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Chapter 6

ANIMAL-BASED CONTROL ALGORITHM FOR NATURAL VENTILATION IN PIG HOUSES

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Abstract

Introduction

Literature

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ANIMAL-BASED CONTROL ALGORITHM FOR NATURAL VENTILATION IN PIG HOUSES

C.E. van 't Klooster[1]

Abstract

An algorithm is developed for environmental control in pig houses with natural ventilation. This controller requires input of animal data instead of input of climate setpoints. The controller includes a growth model for prediction of pig weight and feed intake and a heat balance model at animal level for determination of climate setpoints. The algorithm uses measurement of air exchange based on the carbon dioxide balance. Therefore the algorithm can be used in pig houses with natural ventilation. The control of air flow in pig houses allows for an energy-efficient use of heating systems in pig houses with natural ventilation.

Introduction

Environmental control in pig houses is one of the tools to achieve good performance of the pigs. Both the thermal environment of animals and the air quality have to be controlled. The thermal environment can be described in terms of heat production of animals in combination with heat exchange of pigs with their environment by convective processes, by radiation, by conduction and by latent heat exchange. Air quality in pig houses is the degree to which the room air composition conforms the composition of ambient air. Deviations in air composition in pig houses may include increased levels of carbon dioxide, ammonia and other volatiles as well as viable and inert particles suspended in air.

Control of air quality is normally based on maintaining some minimum air exchange in the house. This minimum air exchange is supposed to dilute undesirable constituents, being produced in the house, to acceptable concentrations. On-line monitoring of a range of gases and vapors is expensive and not practiced in production units. At best the concentrations of some of the air components are determined occasionally.

Control of the thermal environment in pig houses is generally based on a temperature setpoint. Possible control actions are supplementary heating or change in ventilation rates. A temperature sensor is used to measure the deviation from the setpoint. The position of the sensor is important when incomplete mixing of air and heat is possible (Choiniere et al., 1991).

Control of airflow is necessary in pig houses with natural ventilation when heating costs have to be minimized. Estimation of airflow in pig houses with natural

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ventilation is possible with a carbon dioxide model, by modelling carbon dioxide production and by measuring carbon dioxide concentrations (Van 't Klooster and Heitlager, 1994).

In this paper an algorithm is presented for control of airflow and temperature in pig houses with natural ventilation, its setpoints are derived from animal data.

Literature

To reduce energy costs in pig housing the theory on thermal buoyancy and wind influence has been developed to use natural ventilation (Bruce, 1978, Strom and Morsing, 1984; Bruce, 1986; Brockett and Albright, 1987; Foster and Down, 1987; Van 't Ooster and Both, 1988; Bartussek, 1989; Zhang et al.,1989), as discussed in chapter 2. The aim of temperature control is achieved by automatic adjustments of the ventilation openings. Performance checks on full-scale occupied livestock housing have concentrated on temperature control (Barrie and Smith, 1986; Burnett and MacDonald, 1987; Menesses and Bruce, 1987). No reports on climate control with actual measurement of air flow in livestock housing with natural ventilation have been found. In case of heat deficiency the air flow must be controlled when supplementary heat from fossil fuel is supplied. The algorithm described in this paper offers a solution for this type of livestock building.

Controllers

The use of electronic controllers offers an advantage over conventional thermostats as feed-forward mechanisms can be used to adjust setpoints in processes like heating and ventilation. Electronic controllers offer the advantage that control strategies can be implemented that include optimization at farm level (including production costs and returns) instead of only at process level (Challa and van Straten, 1993). Feed-forward control can be used as an addition and improvement in accuracy of conventional feed-backward control (Tantau,1985). These mechanisms have shown the potential to reduce energy consumption in pig houses with mechanical ventilation and heating systems (DeShazer et al.,1987). Electronic controllers with feed-forward mechanisms have also shown to be able to control humidity in poultry houses better than conventional controllers (Allison et al.,1991). The advantages of including feed-forward mechanisms can only be realized when models to predict heat and air contaminant production are included in a climate control algorithm. Sufficient knowledge is available to estimate the production of the animals and has been included in the algorithm. A further improvement in accurary of control can be expected when a model for prediction of ambient weather conditions, like temperature and radiation would be included.

The use of carbon dioxide sensors has shown to function quite well in the climate control in greenhouses, where carbon dioxide levels are monitored to optimize carbon assimilation processes in plants (Gieling,1980; Hanan,1985). A carbon dioxide controller for greenhouses has even been developed as a part of a multi-tasking system for a host-computer (Roy and Jones, 1988). The use of gas balances in determination of ventilation rates is well known and widely used in ventilation tests in residential and occupational buildings (Hitchin and Wilson,1967). The use of a carbon dioxide sensor and balance in the control algorithm can therefore be expected to function satisfactory in a pig building.

Available climate controllers require operators to enter setpoints for temperature and amounts of ventilation (Boon, 1984; Doyle, 1986). The control characteristics of such controllers have shortcomings (Berckmans and Goedseels, 1986). Moreover, a lot of incorrect settings in the controllers are found in practice (Berckmans et al., 1988). The animal performance can vary as strong between producers using similar climate control systems as between producers using different systems for climate control (Geers et al., 1984). Pig producers have knowledge on production and health of pigs. It would therefore be desirable to use this knowledge within the controller to determine setpoints and control the climate. The pig producer could be informed and change settings when desirable but not be left responsible for providing information that he may not understand.

The choice of climate setpoints by an operator who fully understands the controller is normally based on general guidelines that do not use historic data, but may include knowledge on control system behaviour. The selection of these setpoints can be done by a computer as shown for greenhouses (Jones et al.,1988). The algorithm presented in this paper selects the climate setpoints based on pig data supplied by the operator. The operator is informed on the calculated climate setpoints and on the actual measurement of climate data. In practice the operator should be encouraged to update the controller with adjustments in animal data and must be given an opportunity, as an advanced option, to adjust climate setpoints, to allow for personal preference and unforeseen conditions.

In feed-backward controllers in pig houses the proportional controller is widely used. Time-proportional control has been used successfully in poultry houses (Reece et al., 1987). Electronic controllers can use PI and PID control strategies through software. This offers a low-cost possibility to improve control accuracy. The use of PID-controllers requires proper settings of time-constants and gain factors. Emperical methods are often used to select these variables (MacDonald et al., 1989). PID-controllers have been used to control temperature and humidity in animal buildings (Zhang, 1989).

Thermal setpoints

Heat production and heat loss of pigs are equally important in the energy balance of a pig. Mount (1974) introduced the concept of thermoneutrality. Within the thermoneutral zone, a temperature range between the so-called lower and upper critical temperatures, a pig can adjust its heat losses to its heat production, without consequences for the feed intake. Adjustments in heat loss can be made by vascular constriction or dilatation in the vessels near the skin in the lower part of the thermoneutral range, also called comfort zone. Further increase in heat loss may be achieved by panting or by alterations in behavior, like lying posture, huddling or wetting of skin. Below thermoneutrality more heat is necessary to maintain body temperature and feed consumption will increase without necessarily resulting in an increase in growth. This concept is used to model the heat production and critical temperatures of growing pigs (Bruce and Clark, 1979). Refinements of and adaptations to this model have been made that included a variable skin temperature and the modelling of the upper limits of thermoneutral and comfort zone (Van Ouwerkerk, 1988). Within the thermoneutral zone the heat production can be calculated from the feed intake and the body weight of growing pigs. Below the lower critical temperature the heat losses are calculated in terms of convective, radiative, conductive and latent heat losses.

Air quality setpoints

Pigs produce carbon dioxide and water vapor and require oxygen. Without ventilation these concentrations change to unacceptable levels. High carbon dioxide levels may have detrimental effects on pigs (Muehling, 1970). Low humidity levels may cause respiratory problems (Gebauer, 1969), whereas high humidity levels may provide an ideal atmosphere for undesirable micro-organisms (Kaaden, 1980). Other gaseous contaminants in pig houses are formed in pig manure. Ammonia and hydrogen sulfide are known constituents of air in pig confinement buildings that have negative effects on humans and animals (De Boer and Morrison, 1988). Suspended solid particles may also be produced (Heber et al., 1988) in pig houses and in particular endotoxins (Donham, 1991) and glucans may harm animals and humans. In practice a maximum carbon dioxide concentration is often recommended, whereby carbon dioxide levels are used as a tracer for air flow (Van 't Klooster et al., 1991).

Material and methods

Hard- and software

An algorithm was developed using Turbo Pascal 5.5 as a programming language and standard Turbo Async routines for communication through the serial port. A PC was used to run the algorithm. The human interface was a keyboard and a terminal. The I/O interface between the hardware to control the climate in a pig house and the PC was a datalogger (Datataker 100I) connected to a serial port of the PC. The datalogger served as an A/D convertor for the temperature sensors (copper-constantan thermocouples, accuracy: ±0.5°C) and carbon dioxide concentration in room air (Horiba infra-red spectrometer, accuracy: ±50 ppm), had digital input (door sensor), digital output (heater switch) and analog outputs to the southern and northern ventilation openings.

Ventilation system

In the natural ventilated pig house an electrical heater with a capacity of 9 kW was used. For ventilation two ventilation openings in the side walls and an open ridge were used. The open ridge was kept in a fixed position. Both side openings were controlled by the PC-based system and each one could independantly be opened between 0 and 80%.

Pig house

The climate controller was implemented in a compartment for weaned piglets, where the all-in all-out system is used. The room was divided into 6 pens, 1.25 by 2.65 m each, providing place for 11 piglets. Above the solid floor a cover prevents draughts of cold air from falling on the piglets. Metal slats were used. The manure pit was 45 cm deep. Pen separations were solid along the solid floor and an open trellis-work above the slats. In case piglets foul the solid floor a covered small portion of slats against the wall can be opened. The solid floor was slightly rounded. Feed and water were provided ad-libitum in hoppers and nipples located above the slatted floor. Piglets were brought in at a weight of approximately 7.5 kg (26 days old). The first piglets were removed at a weight of approximately 20 kg (extra 35 days).

Results

An algorithm has been developed that requires input on animal data at the start of a batch rearing period for all-in all-out systems for growing pigs. The algorithm calculates its own setpoints. Furthermore it predicts data of animals on subsequent days. Airflow measurement in houses with mechanical ventilation is relatively simple, in this algorithm an air flow measurement model for pig houses with natural ventilation has been included. The main layout is given in figure 1.

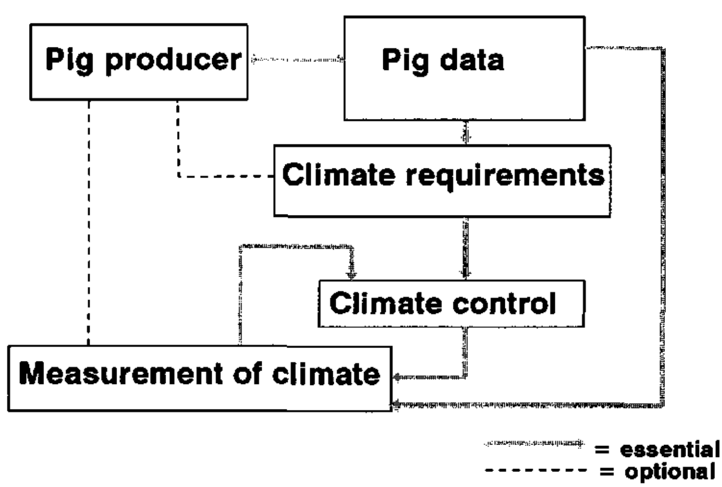

Figure 1. Preferred information flow between producer and climate.

<u>Animal data</u>

To calculate setpoints for the thermal environment of pigs some basic data are necessary. Weight and feed intake are the most important, but these data are not constant during the growing period of animals. Some animal data that influence the climate requirements are fairly constant and do not require daily updating.

This is the case for groupsize (contact surface with penmates) and deep-body temperature. The same holds for some parameters related to housing type with effects on climate requirements, like type of floor, temperature of drinking water, insulation of floor, ceiling temperature, etc. For weight and feed intake, it is cumbersome to make daily adjustments manually. Curves could be used. Another technique that can be used is a prediction model for pig growth. In this algorithm the model of Whittemore (1976) has been used for this purpose as it is accurate enough and does not need data on all amino acids but requires only digestible protein content of feed as input. The Whittemore model is based on pigs kept within their thermoneutral zone. Practical guidelines for temperatures often comply with these recommendations (Van 't Klooster et al., 1989). The algorithm will have to provide a climate that satisfies these criteria. Therefore the processing of animal data can be based on the Whittemore model. See figure 2.

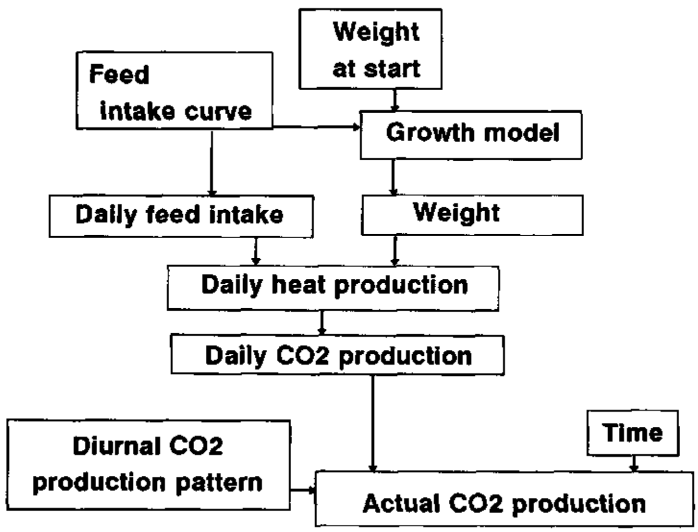

Figure 2. Diagram with animal data.

Thermal setpoints

The thermal requirements are calculated using the equations given by Bruce and Clark (1979) and by Sterrenburg and Van Ouwerkerk (1986). The heat production within the comfortzone is assumed to be constant, that is the thermoneutral heat production (HP). Heat losses can be calculated by physical laws for conduction, convection and radiation, assuming a fixed latent heat production when the thermal resistance of pigs is known. The maximum thermal resistance (vascular constriction) of pigs is used for these conditions. Heat losses increase with decreasing temperatures. The lower critical temperature is found where the thermoneutral heat production equals the physically calculated heat losses with maximum thermal resistance of pigs. The upper value of the comfortzone is found in a similar way, by using minimum thermal resistance in the pigs (vascular dilatation) and equaling this to the thermoneutral heat production. See figure 3.

For the determination of the physical heat losses (HL) the skin surface has to be known. The skin surface of pigs is calculated from their weight. The skin surface partly contacts the floor, partly contacts other skin of the pig itself or skin of penmates, the rest of the skin surface is assumed to be in contact with air. Contact surface with walls is not taken into consideration. The relative distribution of the skin surfaces depends on lying behaviour of the pigs and is corrected when pigs are outside the comfortzone. When pigs are standing, it is assumed that all skin is surrounded by air and the rest is neglected. The percentage of time that pigs are standing, decreases with an increase in weight.

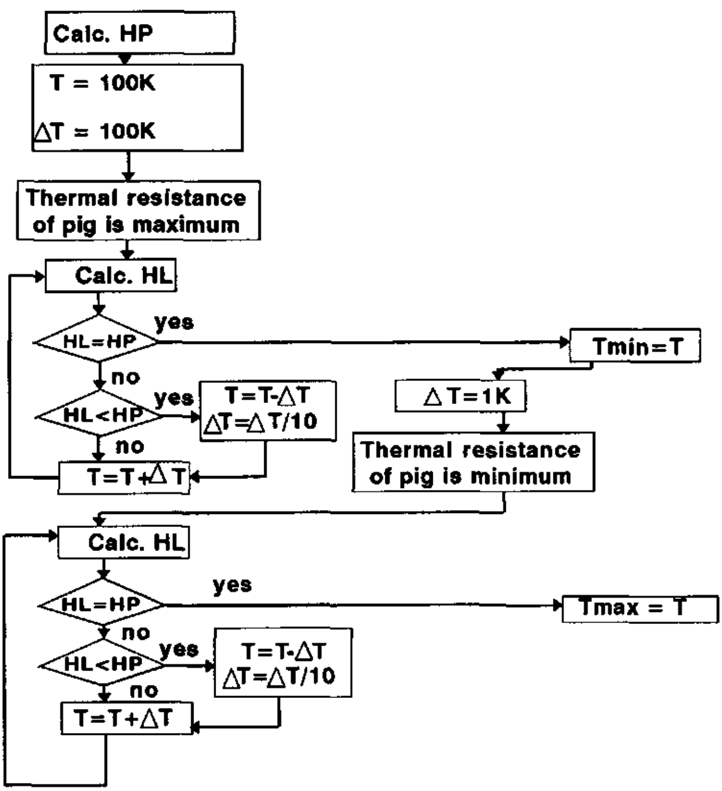

Figure 3. Determination diagram for lower and upper desired temperature in pig house (Tmin and Tmax).

Climate control

Temperature can be measured by a sensor like a thermocouple or Pt100 type.

Airflow in pig houses can be estimated using a carbon dioxide balance. This requires a device to measure on-line the carbon dioxide concentration in the pig house. In houses with mechanical ventilation cheaper solutions are possible with a ventilation rate sensor. Heating can be necessary in pig houses and should be part of the climate control system. Cooling pig houses is normally achieved by increased ventilation. The climate control in the algorithm is indicated in figure 4. In this algorithm the carbon dioxide concentration (CO_2) is measured as indicator of air quality and should not exceed a certain limit ($CO_{2,max}$). The carbon dioxide production is combined with the concentration to calculate air exchange. Heating systems are normally on/off systems. A time-proportional PID controller is included for the heating system to achieve fast and correct response in dynamic situations. The ventilation openings are operated by a PID controller. Stability of air flow patterns is considered important. The air flow is only adjusted when temperature departs from the desired range or when air quality becomes unacceptable. Whenever the control system cannot meet the climate requirements, an alarm system must come in operation to alert the pig producer.

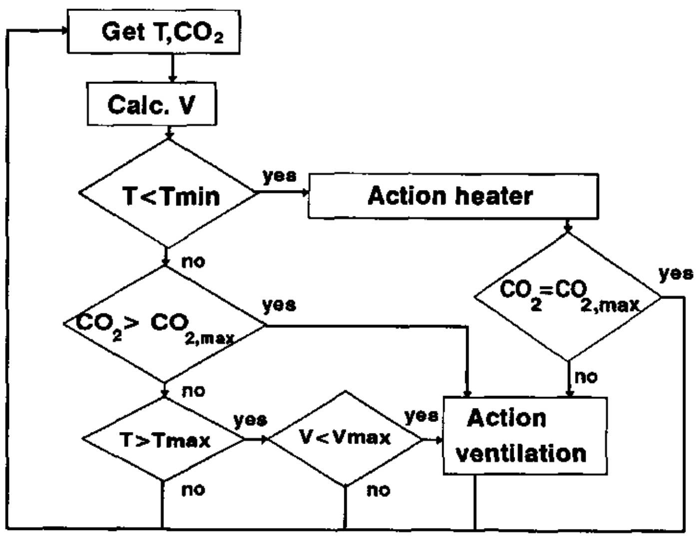

Figure 4. Diagram of climate control in pig house with airflow control and natural ventilation.

Algorithm output

Based on an initial weight and a feed intake curve the algorithm can determine daily growth, feed intake and body weight as in figure 5. Manual adjustment is always possible. The animal data are transformed into thermal setpoints, data from figure 5 will result in the curves shown in figure 6. With increase in feed intake and body weight, the lower and upper setpoints for thermal control will decrease. Apart from the thermal setpoint, control of air quality is necessary and a setpoint for the maximum carbon dioxide concentration can be entered in the algorithm. In figure 7 the actual climate resulting from the algorithm is given for a day when heating was required to maintain a temperature within the lower and upper setpoints. In figure 8 the actual climate in a pig house is given for a particular day where at 10:30 h extra heating was started to follow the room temperature in a situation where the upper setpoint becomes the main variable to be controlled. In both cases a maximum carbon dioxide concentration of 1700 ppm was used as a setpoint for control of air quality.

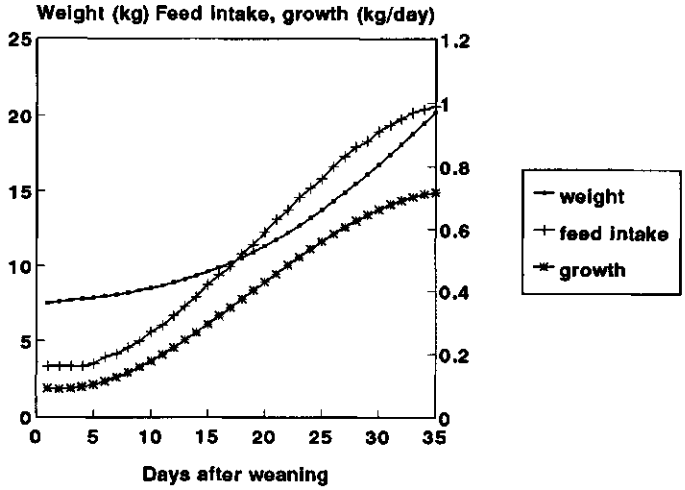

Figure 5. Body weight, daily growth and feed intake of weaned piglets as determined by the algorithm.

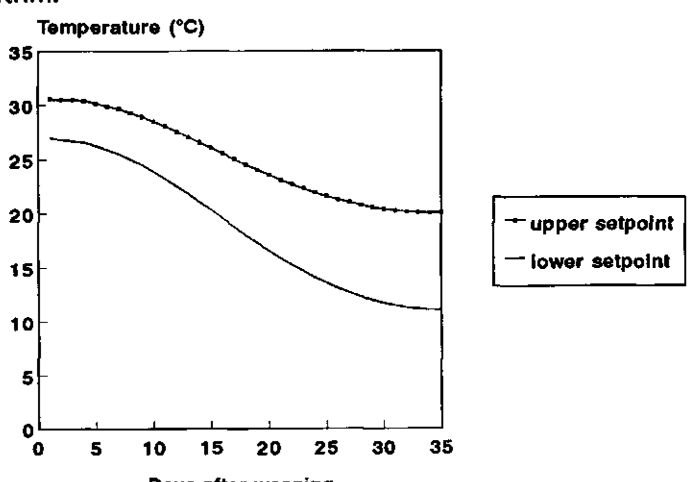

Figure 6. The lower and upper thermal setpoints found by the algorithm for temperature control in a pig house with weaned piglets as in figure 5.

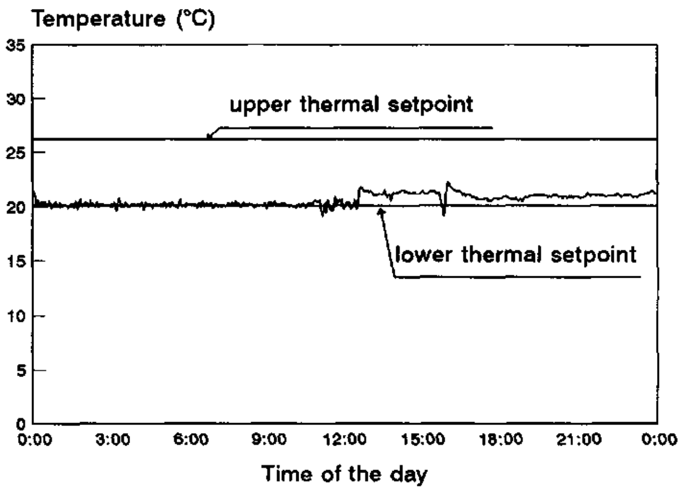

Figure 7a. Actual room temperature and lower and upper thermal setpoint in the building as a function of time.

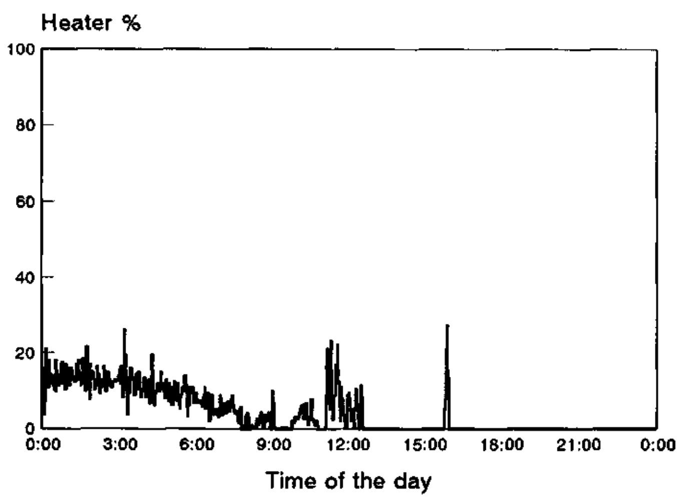

Figure 7b. The utilization of the heating capacity in the building as a function of time.

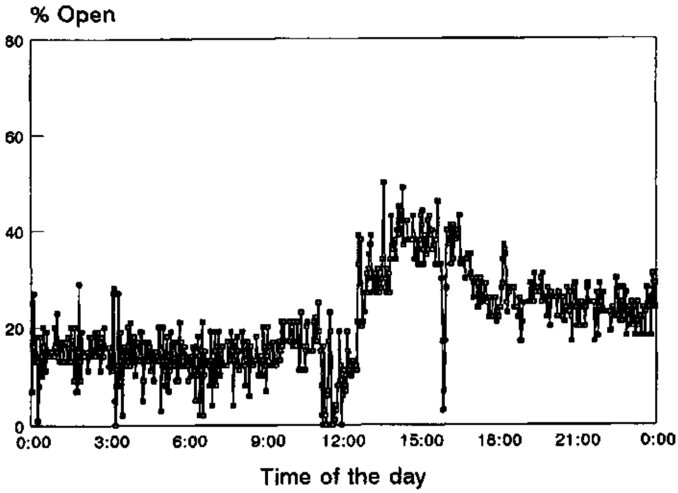

Figure 7c. The position of the ventilation openings in the building as a function of time.

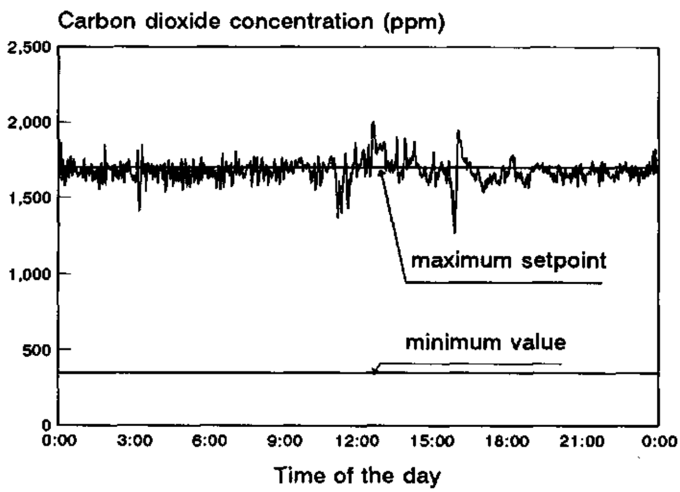

Figure 7d. The resulting level of carbon dioxide in the building as a function of time.

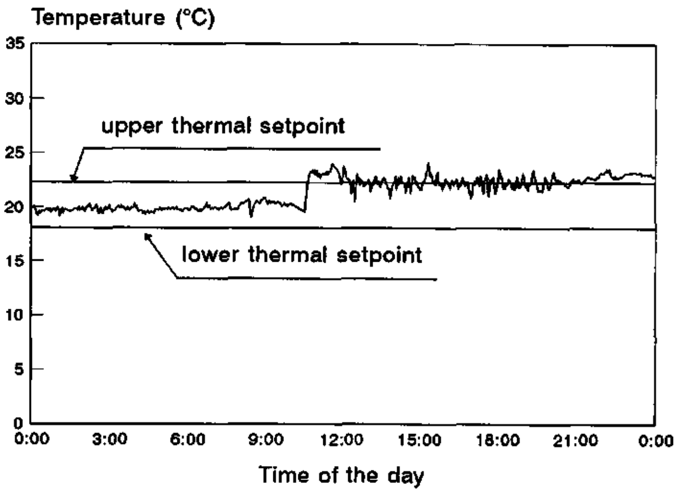

Figure 8a. Actual room temperature and lower and upper thermal setpoint, when heating was switched on at 1030h in the building as a function of time.

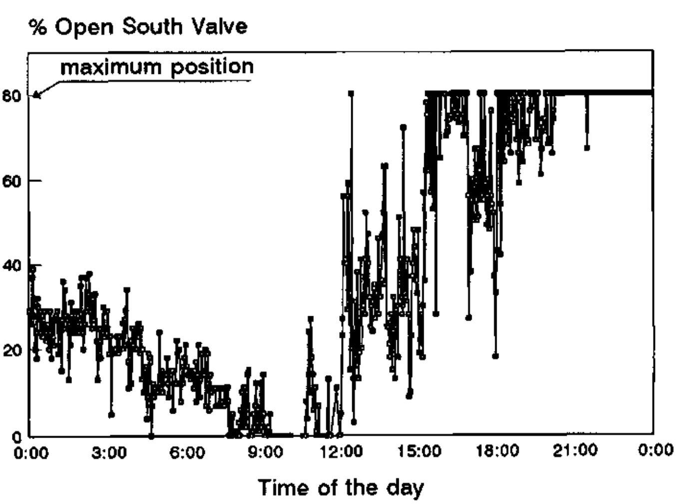

Figure 8b. The corresponding position of the southern ventilation opening in the building as a function of time.

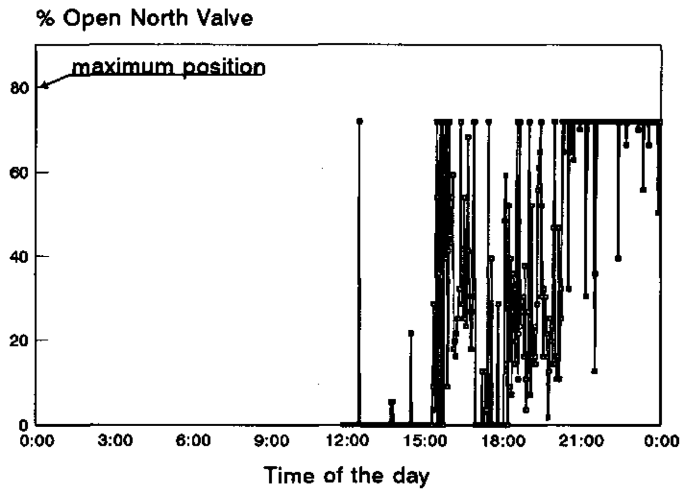

Figure 8c. The corresponding position of the northern ventilation opening in the building as a function of time.

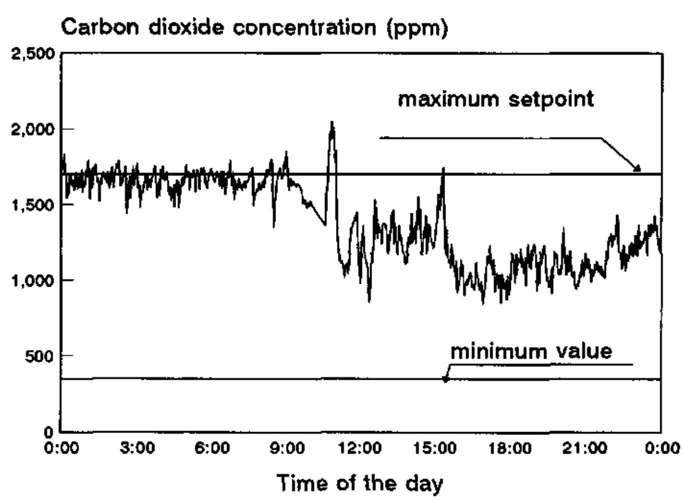

Figure 8d. The resulting level of carbon dioxide in the building as a function of time.

In figure 7 the lower setpoint for temperature was 20.1°C. The average room temperature during that day was 20.6°C, with a standard deviation of 0.5°C and reaching a minimum value of 19.1 and a maximum value of 22.2°C. The maximum setpoint for carbon dioxide was set at 1700 ppm. An average carbon dioxide concentration of 1680 ppm was realized with a standard deviation of 80 ppm, a minimum value of 1290 ppm and a maximum level of 2010 ppm. In figure 8 the performance of the control algorithm with regard to the upper temperature setpoint can be evaluated for the period between 12:30 pm and 8:15 pm when the building has warmed up and reaches the maximum temperature setpoint. After 8:15 pm the ventilation is constantly kept at maximum levels and, with uncontrolled heating at full capacity, temperature falls outside the control range of the algorithm. The average room temperature between 12:30 pm and 8:15 pm was 22.3°C, with a standard deviation of 0.5°C and a minimum value of 20.8 and a maximum value of 24.2°C, while the upper temperature setpoint was 22.4°C.

Discussion

The input of animal data requires knowledge of numbers of animals, animal weight and animal feed intake. Numbers of pigs are easy to establish, but the weight and feed intake may create some problems. Although both can be found in practice by weighing, these data are usually not available and have to be estimated. The algorithm initiates and updates values for weight and feed intake, full automatic control based on correct data will not be available until continuous weighing of animals and feed intake is realized.

The accuracy in the translation from animal data into climate setpoints depends on the accuracy of the heat balance. Sterrenburg and Van Ouwerkerk (1986) concluded that the standard deviation in the lower thermal setpoint is approximately 0.9°C. To cope with this uncertainty in setpoints, the algorithm has the possibility to adapt the setpoints, whenever the pig producer observes a lying behaviour of pigs that show signs of thermal discomfort.

The climate control as realized shows that room temperatures can be kept within 1°C of the setpoints and air quality within a 10% deviation of the setpoint for over 95% of the time.

In the algorithm setpoints are kept constant from midnight till midnight. At midnight an automatic update of feed intake and body weight is performed, resulting in a stepwise change in setpoints. In figures 7a and 8a the effect of the decrement in lower temperature setpoint at midnight can be observed. Once more information on the diurnal variations in climate requirements becomes available, the algorithm can be adapted to handle these variations.

The link between animal data and climate control makes it theoretically possible to connect electronic controllers for climate control and feeding. A technical possibility for such a connection would be to link these two controllers to a personal computer with a farm management program. In this way the mutual optimization of these processes can be combined with evaluation of performance with respect to climate and nutrition. However insufficient knowledge is available at this moment to use climate data for evaluation of long-term performance of pigs (Fuchs et al., 1991).

Conclusions

The development of a control algorithm for thermal and airflow control in naturally ventilated heated pig houses makes it possible to control heating costs in these buildings.

The concept of control over heating costs combined with natural ventilation makes it possible to save energy for climate control when compared with other alternatives for heated pig houses.

An animal-based control algorithm for naturally ventilated pig buildings is feasible when a computer is used for climate control.

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Chapter 7

DYNAMIC MODEL TO TUNE A CLIMATE CONTROL ALGORITHM IN PIG HOUSES

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Abstract
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2. Mathematical Model
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3.1. Model results
3.2. Model responses to control algorithm
3.3 Climate responses to control algorithm
4. Discussion
5. Conclusions
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DYNAMIC MODEL TO TUNE A CLIMATE CONTROL ALGORITHM IN PIG HOUSES

C.E. van 't Klooster, J. Bontsema and L. Salomons[1]

Abstract

Algorithms for environmental control in livestock buildings have to be tuned for optimum response of actuators. For tuning a simple, but dynamic, climate model for a pig house is formulated and validated to predict the environmental changes in a pig house under varying conditions. A control algorithm is included in the model and tuning of the algorithm has been performed with the model. This can serve as a tool to replace empirical tuning in the field. The tuned algorithm was implemented in a climate controller and data on the results are presented.

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Notation

A	surfaces with transmission losses (m^2)
C	production rate of carbon dioxide (kg/s)
c	specific heat ($Jkg^{-1}K^{-1}$)
$[CO_2]$	carbon dioxide concentration (kg/kg air)
D	damping depth (m)
E	difference between setpoint and actual value
H	heat capacity (J/K)
h	enthalpy
n	number of pigs in pig house
O	output of controller to actuator
$\hat{O}$	physical upper or lower limit of actuator
Q	heat production (W)
R	Thermal Resistance (m^2KW^{-1})
T	Temperature (°C)
t	time (s)
V	Volume of room (m^3)
W	Amplitude of temperature wave
w	mass of average pig in pig house (kg)
X	water vapor content of air (kg H_2O/kg dry air)
ϵ	evaporation heat of water (J/kg)
ϕ	phase shift (rad)
θ	mass flow (kg/s)
ρ	density of air (kg/m^3)
τ	time constant (s)
ω	rotation frequency temperature wave (rad/s)

Subscripts

a	ambient
b	absorbed by heating system
C	carbon dioxide
d	daily average
D	differentiating
e	extra heaters
g	gas mixture of dry air
h	in pig house
i	incoming
I	integrating
l	latent
m	momentary
o	outgoing
P	proportional
p	pigs
R	rewind
r	radiation
s	sensible
T	tamed differential
t	transmission losses
w	water vapor
y	yearly average
z	depth in soil (m)

1. Introduction

A control algorithm can be a tool to maintain a desired climate environment in a livestock barn. A conventional control algorithm contains a combination of responses by ventilating and heating actuators to reach the particular setpoint of a parameter such as room temperature or ventilation rate. The difference between the measured values and the setpoints of the parameters is processed in a on/off, proportional (P), integrating (I) and/or differentiating (D) action of the actuators. For a smooth, stable and quick response the gain factors (K) and time constants (τ_I and τ_D) for the P, I and D are important. A common procedure to find these values is the empirical determination in the process. In cases with P, I and D actions the Ziegler-Nichols rules are widely used (Cool et al., 1991), where with only the P action, the point is found where the system is instable and oscillating with a constant frequency. With a slow process like warming or cooling of a livestock building it may take several hours to measure the response and see whether the system is oscillating for a particular value. This procedure for tuning the control algorithm can give satisfying results (MacDonald et al., 1989). The procedure would be time-consuming when it would have to be carried out for each livestock building, especially when an algorithm for climate control contains several PID controllers. As building dimensions, number of animals per house, fan and heater capacities, etc. vary from house to house, the values which work well in one barn will not necessarily give good results in another barn. It would either save time or give better control when the tuning of the control algorithm could be done with a software package.

This paper describes this method. A model is presented that simulates the climate in a house. With dynamic ambient conditions and heat storage in the building, the climate in the livestock building is a dynamic process. A particular climate control algorithm has been linked to the model. Tuning the controller by simulation of the climate response for various values of gain factors and time constants can then be carried out within a short time span.

2. Mathematical Model

The model assumes the space in the building to be one homogeneous volume. Also the volume is assumed to be constant. With growing pigs and varying levels in the manure storage, this is not correct, but the manure storage is usually under a slatted floor and good ventilation systems intend to ventilate effectively the building volume above the slat and not to involve the air volume under the slats in the air circulation pattern. The building shell is split in different layers. The model uses an energy, a mass, a water and a carbon dioxide balance to predict values of parameters over time (Fig. 1).

The energy balance of a particular room is made up by sensible and latent heat exchange through ventilation, by sensible heat exchange through the building shell and by sensible and latent heat production in the house. The energy balance is given by Eqn. 1.

$$\frac{d}{dt}(V\rho_h h_h)=\theta_i h_a-\theta_o h_h-Q_t+Q_s n+Q_l n+Q_e \qquad (1)$$

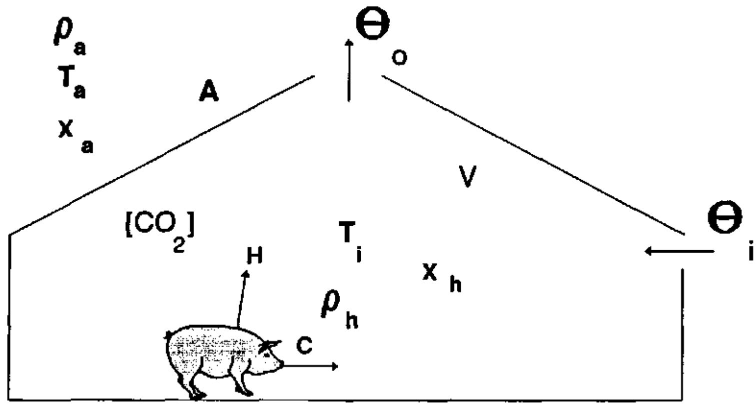

Figure 1. Heat, moisture and carbon exchange in a livestock building.

Differentiation of the right-hand term of Eqn. 1. results in Eqn. 2.

$$\frac{d}{dt}(V\rho_h h_h)=V\rho_h\frac{dh_h}{dt}+h_h\frac{d}{dt}(V\rho_h) \tag{2}$$

The enthalpy of the volume of air will be a function of temperature (T) and moisture content (X) as in Eqn. 3.

$$h=c_g T+\epsilon X+c_w TX \tag{3}$$

This equation for the enthalpy can be differentiated as shown in Eqn. 4.

$$\frac{dh}{dt}=\frac{\partial h}{\partial T}\frac{dT}{dt}+\frac{\partial h}{\partial X}\frac{dX}{dt} \tag{4}$$

Eqn. 3 results in the partial terms given in Eqn. 5 and 6.

$$\frac{\partial h}{\partial T}=c_g+c_w X \tag{5}$$

$$\frac{\partial h}{\partial X}=\epsilon+c_w T \tag{6}$$

The mass balance of the air in the house is mainly determined by incoming and outgoing air. In terms of mass the production of gases and vapours is neglectible to the total air mass in the building and is not included in the mass balance (Eqn. 7).

$$\frac{d}{dt}(V\rho_h)=\theta_i-\theta_o \tag{7}$$

The water vapour balance of the air inside the room includes latent heat production by the animals, but does take into account any condensation to or evaporation from surfaces (Eqn. 8). The water vapour balance has only a small influence on the room temperature.

$$\frac{dX_h}{dt}=(\theta_i X_a-\theta_o X_h+\frac{Q_l n}{\rho_h \epsilon_h})/V \tag{8}$$

From Eqn. 1 to 8 the equation for the house temperature can be given as Eqn. 9.

$$(c_g+c_w X_h)\rho_h V\frac{dT_h}{dt}=Q_s n+Q_e-Q_t+((\theta_o X_{h_{\theta_i}} X_a)\frac{c_w}{V}-\frac{c_w Q_l n}{\rho_h \epsilon_h V})T_h+\theta_i(h_a-h_h)-\frac{\epsilon_h}{V}(\theta_o X_h-\theta_i X_a) \tag{9}$$

The carbon dioxide balance for a pig house has been described by Van 't Klooster and Heitlager (1994) as:

$$d\frac{[CO_2]}{dt}=\frac{\theta_{i,C}}{V}+\frac{C_m}{V}+\frac{\theta_{e,C}}{V}-\frac{\theta_{o,C}}{V} \tag{10}$$

The total heat production of the animals is associated with the carbon dioxide production (Van 't Klooster and Heitlager, 1994) as in Eqn. 11.

$$Q_{s+l,m}=1.09*10^7 C_m \tag{11}$$

The fraction of latent heat can be found with Eqn. 12 given by Aarnink and van Ouwerkerk (1990).

$$Q_l=(0.1+3.54*10^{-7}T^4)Q_{s+l} \tag{12}$$

Heating systems in livestock buildings are usually on-off systems. The response in heating power released by the heating system to the absorbed power is influenced by the heat capacity and heat transportation within the heating system itself. It can be described as a first order process (Zhang et al., 1992). It can also be described as a second order process as in Eqn. 13 to describe the released heat. In case of a first order process τ_{h2} would be equal to zero in Eqn. 13.

$$\tau_{h1}\tau_{h2}\frac{d^2Q_e}{dt^2}+(\tau_{h1}+\tau_{h2})\frac{dQ_e}{dt}+Q_e=Q_b \tag{13}$$

The transmission losses of the building have been modelled by splitting the surfaces in five different layers. The temperature of layer x will be determined with Eqn. 14.

$$\frac{dT_x}{dt}=A_{i,x}\frac{T_i-T_x}{HR_{x,i}}+A_{o,x}\frac{T_o-T_x}{HR_{x,o}} \tag{14}$$

The floor surface will transmit heat to the soil. The soil temperature varies with depth, texture, and season. The model uses the annual cycle in the soil temperature as given by Wesseling (1985) and is given in Eqn. 15, where t is time in seconds after the turn of the year, and damping depth D is taken as 3.15 m and depth z is taken as 0.9 m.

$$T_{soil,z}(t)=T_{soil,z,y}+We^{z/D}\sin(\omega t+\phi) \tag{15}$$

The effects of solar radiation on the roof can be accounted for in the model when data on the temperature in a layer of the roof are available.

3. Results

The model has been implemented without and with a control algorithm (Van 't Klooster, 1994) using the STEM (Simulation Tool for Easy Modeling) package (Anon., 1991). The model is simulated with the 4th order Runge-Kutta algorithm. Integration step is 1 second in the model simulation and 30 seconds in the simulation of the control algorithm. The algorithm is also implemented in a climate controller of a pig house with natural ventilation. Simulated and actual climate results are presented.

3.1 Model results

The model can simulate the effect of the heating system on room temperature. For an electric fan heater the simulated and measured room temperature in an unventilated, empty pig house are given in Fig. 2. The heater, absorbing 9000 W, is simulated in this example as a second order process with time constants τ_1 = 50s and τ_2 = 420s. A simulation of the room temperature in a pig house fully stocked with pigs, uncontrolled natural ventilation and with a heating system that is thermostatically controlled is given in Fig.3. The simulation predicts room temperatures that are up to 2°C higher than measured room temperatures after the heating system is switched on. The dynamics in the temperature of the simulation is similar to the measured temperature. For the purpose of tuning a control algorithm the dynamics of the model are important and the model gives satisfactory results. The measured value of the temperature is based on the average of two temperature sensors, one located at animal level and one located at a height of 1.5 m (Fig. 4). Combining Fig. 3 and 4 shows that, when the heating system is in operation, the temperature at 1.5 m height is between 3 and 4°C higher than between the animals. The temperature of the sensor at 1.5 m height reaches higher values than the simulated temperature. The heater throws a jet of hot air in the house and when the air flow pattern in the house would direct part of this jet to a particular point where a sensor is located, a higher than average room temperature will be read. In situations with high temperature differences, caused by the heat sources in the house, and unknown air flow patterns there would be several sensors required to measure a correct value of the average room temperature, which confirms conclusions by Choinière et al. (1991).

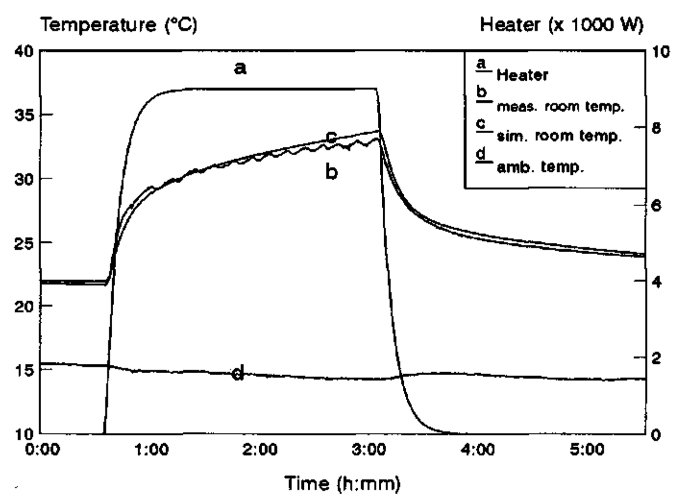

Figure 2. Measured and simulated room temperature in an unventilated and empty pig house in response to an electric heater as a function of time.

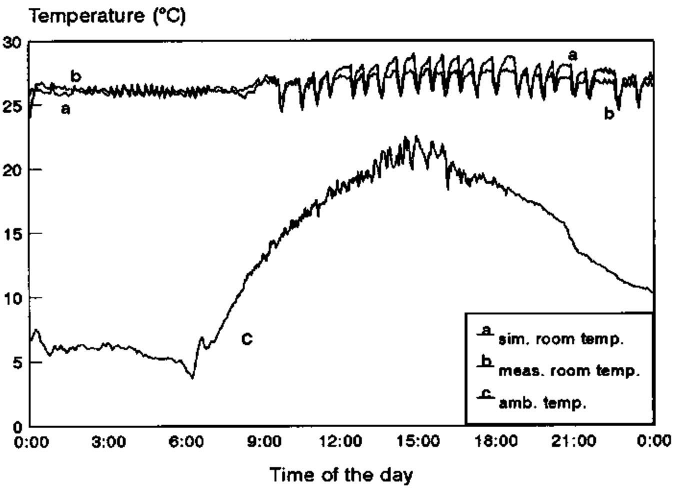

Figure 3. Measured room temperature, measured ambient temperature and simulated room temperature in a natural ventilated pig house without airflow control but stocked with animals in response to an electric heater as a function of time.

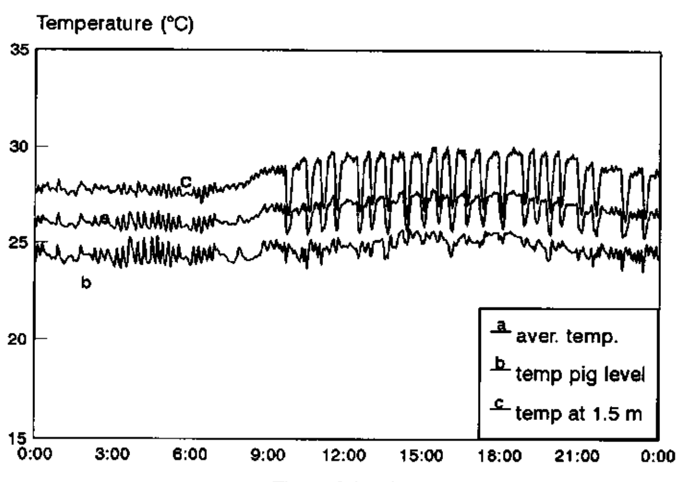

Figure 4. Room temperatures at animal level, at 1.5 m height and average value as used in figure 3 in a ventilated and stocked pig house at two locations as a function of time (s).

3.2 Model responses to control algorithm

An algorithm for temperature and ventilation control in pig houses that can be used in combination with natural ventilation as described in chapter 6 is given in Fig 5. Four PID loops and an on/off controller for the heater are included in the algorithm. Controller 4 in Fig. 5 is implemented as a PID controller as this improves accuracy when this controller and the ventilation openings are placed in a control circuit within a cascade circuit.

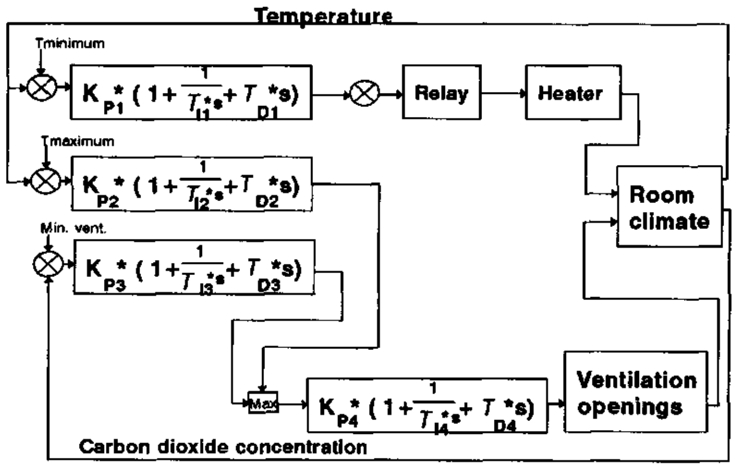

Figure 5. Algorithm for control of temperature, air quality and ventilation rate for a pig house with heating and natural ventilation.

The output to a actuator (O) can exceed the physical limits of this actuator, while such a state continues, the output of a PID controller to the actuator will be build up by the integrating term and deviate further from the physical limit. The actuator will only start to move when O reaches values within the physical limits of the actuator. In some cases this is not desired. When the ventilation openings are opened up to the maximum position at a certain temperature, an integrating term builds the output of the controller up when temperature rises further. This may result in a very slow response when ambient temperature suddenly drops as may happen with thunderstorms. To prevent such situtations the integrating action in PID loop 4 is limited with an anti-windup construction as described by Morari (1993) (Eqn. 16), where $\hat{O}$ stays at the minimum or maximum value of O when O would run out of bounds. The maximum position of the ventilation openings in this situation was 80%, as 100% opening could not be realized by the hardware.

$$O_t = K_P[E_t + \frac{1}{\tau_I}\int_0^t (E_t - \frac{\tau_I}{K_P\tau_R}(O_t - \hat{o}_t))dt] \tag{16}$$

This anti-windup construction limits the integrating term while the actuator is in minimum or maximum position. Full differentiating action of controllers may result in strong and frequent adjustments of the output to the actuators. A practical solution to reduce the resulting wear and tear of actuators is to use a tamed D action as in Eqn. 17 and 18.

$$O(t) = \frac{K_P\tau_D}{\tau_T}E(t) + p(t) \tag{17}$$

$$\frac{dp}{dt} = -\frac{1}{\tau_T}p(t) + \frac{1}{\tau_T}(\frac{K_P\tau_D}{\tau_T})(\frac{\tau_T}{\tau_D} - 1)E(t) \tag{18}$$

In practice τ_T is given values between $0.2\tau_D$ and τ_D (Cool et al., 1991). In the simulation a realistic noise level in input is necessary to create realistic noise in output parameters. To generate noise on the airflow through the ventilation openings data on wind speed and wind direction of several days were taken ad random and translated to noise on the airflows. The values for the controllers in Fig. 5 are given in table 1. In all four cases τ_T is given a value of $0.2\tau_D$.

Table 1. Values for PID controllers in control algorithm as in Fig. 5.

	K_P	τ_I	τ_D	τ_R
PID1	2500	200	20	150
PID2	0.2	75	10	100
PID3	860	20000	25000	20000
PID4	30	1000	100	1000

Simulation responses to the control algorithm are given in Fig. 6 a,b,c and d. In Fig. 6a where the lower and higher temperature setpoints are given, the room temperature reaches the desired setpoint very quick, except when the lower temperature setpoint is set at 29°C, it takes about 40 minutes before the lower setpoint is reached. This is caused by the limited heating capacity and not by the control strategy as can be seen in Fig. 6b. In the period between 04.30 h and 08.00 h, when the lower temperature setpoint is at

23.8°C, the average room temperature is 23.9, having a minimum value of 23.0°C and a maximum value of 24.8°C while the standard deviation was 0.4°C. When subsequently the upper temperature setpoint is lowered to 21°C, it takes about 18 minutes before this value is reached. Again the control algorithm works well, heating is off and ventilation openings are fully open, but the stored heat has to be removed by ventilation before the setpoint can be reached. In Fig. 6c it can be seen that the air quality is kept at the setpoint, which was defined as 0.00316 kg CO_2/kg air (1700 ppm). Average carbon dioxide concentration in the period from 00.00 h till 18.00 h was also 0.0032 kg CO_2/kg air, with a minimum value of 0.0026 and a maximum value of 0.0037 kg CO_2/kg air during this period, the standard deviation during this period was 0.000136 kg CO_2/kg air (70 ppm). The effects of the integral wind-up action can be seen in Fig. 6d where overshoot does not build up, but ventilation openings respond quickly to sudden changes in conditions. The differential action is tamed with τ_T being $0.2\tau_D$ resulting in a fairly smooth running of the ventilation openings (Fig. 6d).

3.3 Climate responses to control algorithm

The climate in a pig house as controlled by the algorithm on a day where temperature remained within the setpoints and no heating was required is given in figure 7 a, b and c. During this day the average carbon dioxide concentration was 1680 ppm, lowest value was 1550 and highest value was 2080 ppm, while the setpoint was 1700 ppm. The standard deviation of the carbon dioxide concentration was 50 ppm.

For a cold day (ambient temperature -5°C till 08.00 h) the climate in the same pig house is given in figure 8 a, b and c. On this particular day heating was necessary all day. While the lower temperature setpoint was 22.0°C, the average realized room temperature on this day was 21.7°C, with a minimum value of 18.7°C and a maximum value of 23.4°C. The standard deviation of the temperature was 0.8°C. The setpoint for air quality was 1700 ppm. Average concentration was 1710 ppm, a lowest value of 1100 ppm and a highest value of 2650 ppm, standard deviation was 190 ppm. When the required capacity of the heater varies, the variation in temperature and carbon dioxide concentration also increases. The heater is equipped with a fan that swithes on and off with the heater. This has a definite influence on the air flow pattern. The capacity of the fan was higher than the average ventilation rate, indicating that the resulting static and dynamic pressure distribution depends on the on/off position of the heater.

The room where the algorithm was implemented had two doors that connected to adjacent rooms, both without control of carbon dioxide concentrations. The peaks in carbon dioxide concentrations may be associated with human passage through doors.

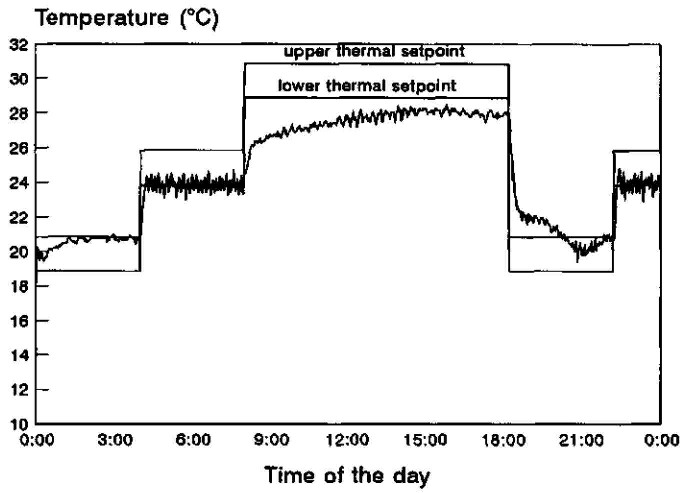

Figure 6a. Simulated response to control algorithm of room temperature.

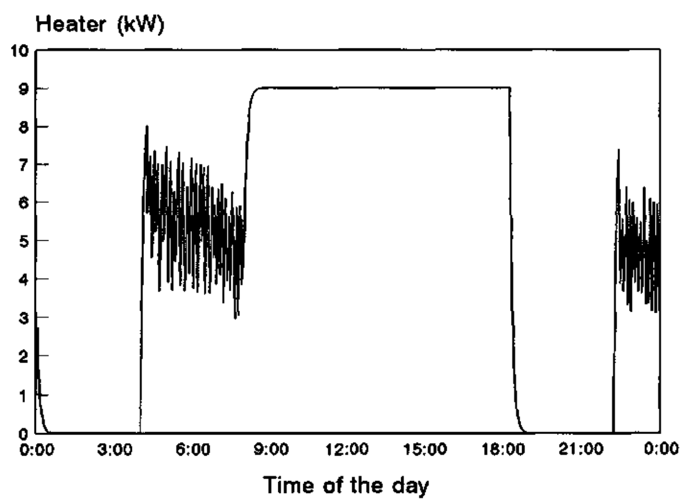

Figure 6b. Simulated response to control algorithm of heater.

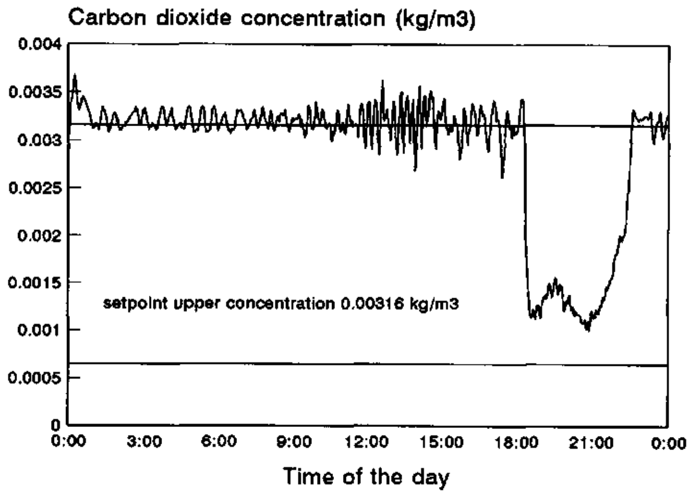

Figure 6c. Simulated response to control algorithm of carbon dioxide concentration.

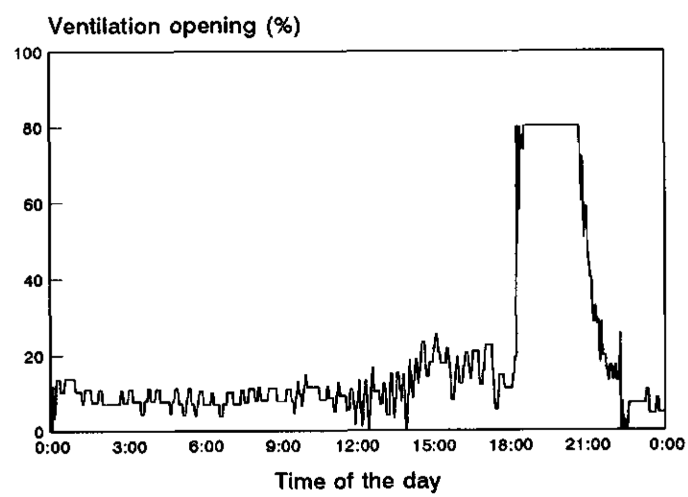

Figure 6d. Simulated response to control algorithm of ventilation opening.

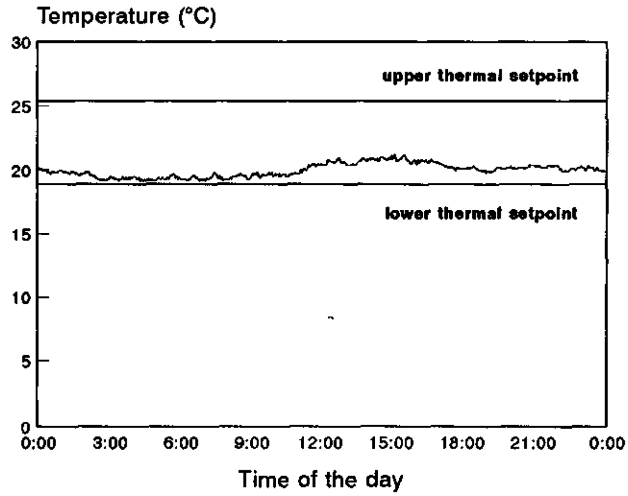

Figure 7a. Response of temperature in pig house to control algorithm on a day with no heating.

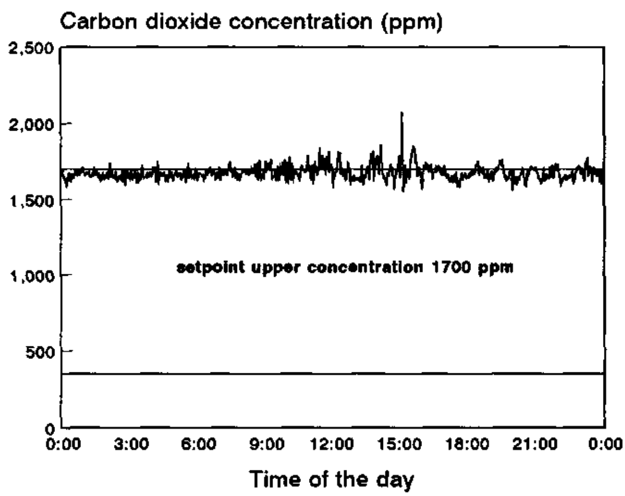

Figure 7b. Response of carbon dioxide concentration in pig house to control algorithm on a day with no heating.

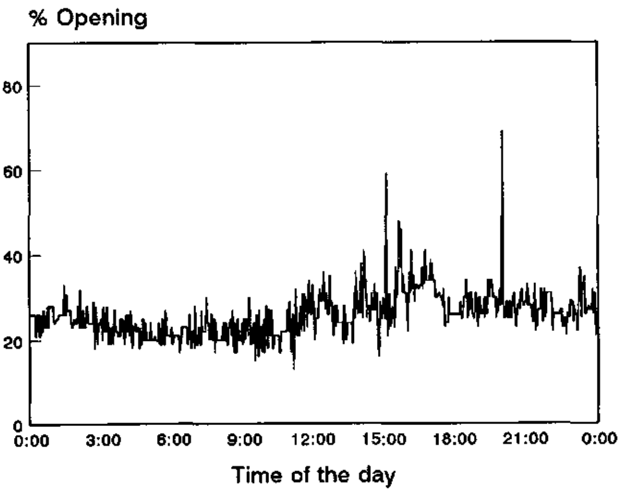

Figure 7c. Response of ventilation opening in pig house to control algorithm on a day with no heating.

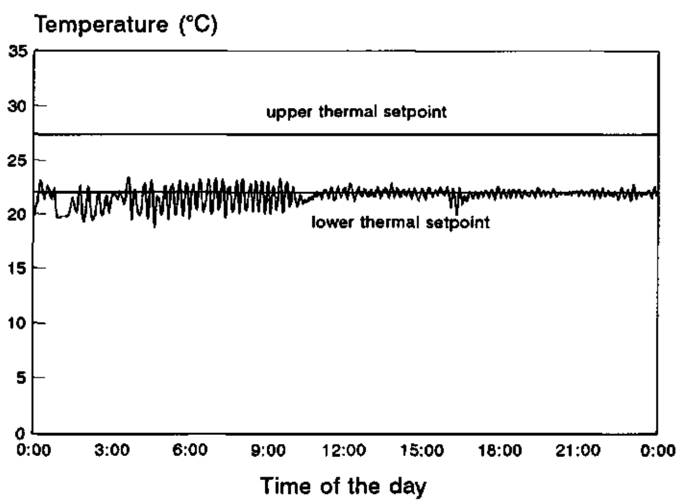

Figure 8a. Response of temperature in pig house to control algorithm on a cold day.

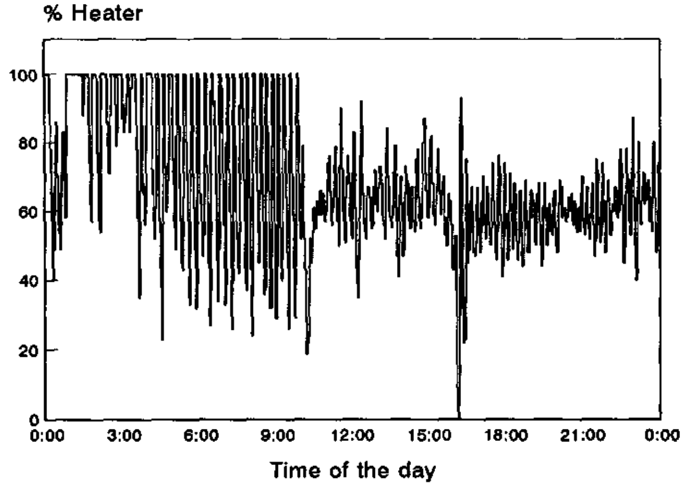

Figure 8b. Response heater in pig house to control algorithm on a cold day.

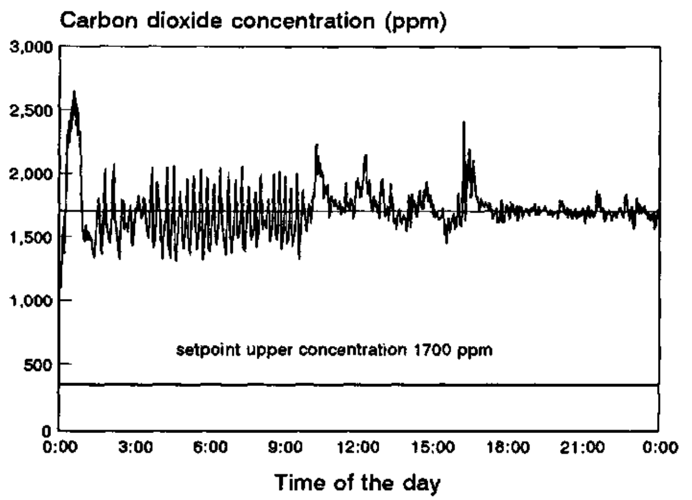

Figure 8c. Response of carbon dioxide concentration in pig house to control algorithm on a cold day.

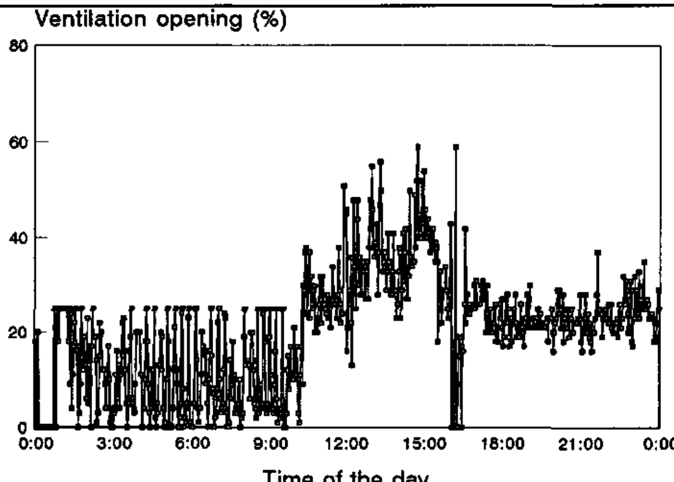

Figure 8d. Response of ventilation opening in pig house to control algorithm on a cold day.

4. Discussion

The results of the simulation and of the actual control show that the gain factors and time constants of the controllers found by the simulation work in a similar way in the real pig house. The model assumes perfect mixing of air in the pig house. The switching of the heater creates variations in heat production and results in variation in ventilation, which is translated into variation in temperature and carbon dioxide concentration. This effect is found both in the simulation results and in the actual climate results. The effect in the house is however larger than the effect in the simulation. From this difference it can be concluded that the assumption of complete mixing is not completely met and influenced by the switching of the heater. A further refinement of the model may account for this effect by defining a volume around the sensor which relates to the average room conditions depending on air flow pattern as done by Berckmans et al. (1992). A further refinement in the algorithm is possible by changing from a on/off heating system to a system with step control.

The dynamics as well as the actual levels of climate parameters show good agreement between simulation results and actual results.

The human interference is not included in the model. In the real building, which is under standard management practices, the climate control will be influenced occasionally by the pig producer e.g. by opening of doors etc. The control algorithm handles this noise in an acceptable way.

5. Conclusions

A dynamic model is presented that can be used to simulate room temperature and carbon dioxide concentration in heated pig houses with natural ventilation.

The model can be used to find gain factors and time constants for PID-controllers in algorithms for control of roomtemperature, air quality and ventilation rate in natural ventilated pig houses.

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Chapter 8

FINAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Final discussion

Final conclusions

Recommendations for further research

References

FINAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Final Discussion

The aim of this study was the development of a climate control strategy that can be used by pork producers. Ventilation and heating are the two basic processes used in climate control in pig houses. Cooling techniques other than ventilation, are hardly used to avoid heat stress. Present technology is directed towards mechanical ventilation, where heating can be combined with controlled ventilation rates or to natural ventilation without control of ventilation rates. Three basic concepts to measure ventilation rates in pig houses with natural ventilation are mentioned: Direct measurement of ventilation flows in the first place. A second concept can be the quantification of the physical forces that cause ventilation and use this to find the ventilation rates. A third approach is the formulation of a balance where one or more terms are generated by ventilation. The balance concept will not give accurate results when ventilation gives only a minor contribution to the equation. Heat processes are relatively well known and a heat balance can theoretically be used. With heavy buildings and large heat capacities temperature response is however pretty slow. Other disadvantages are the potential changes in distribution between sensible and latent heat and the fact that the accuracy of the transmission losses strongly influences the accuracy of the estimated ventilation rate. In a carbon dioxide balance ventilation is a major loss term, what contributes to a relatively accurate estimation of the ventilation rate. A disadvantage is that the production term must be known and in a dynamic situation this production is difficult to measure directly, as storage of carbon dioxide in the room air plays a role. A viable approach to attain the production term is to use zoological knowledge, requiring an integration between technical and zoological disciplines. Hitherto monodisciplinary approaches have been predominant. Manufacturers of climate controllers could up to now supply properly dimensioned technical components and corresponding software but will have to incorporate biological models in their software when they implement a carbon dioxide balance. A second disadvantage of a carbon dioxide balance is the need for a carbon dioxide concentration sensor. These sensors are available but are more expensive than other types like temperature sensors and air flow rate sensors. These extra costs are however compensated by lower energy costs and can therefore be accepted as a consequence of the use of a carbon dioxide balance. In the type of building tested a mean discripancy of 13% was found between the carbon dioxide balance method and the rate of decay of tracer gas method, acceptable for practical purposes. This building had only two ventilation openings. This makes the distribution of tracer gas over the room relatively simple. In the room a high internal heat production rate by animals and heating systems with corresponding intensive convective mixing takes place. Application of the carbon dioxide balance in other livestock buildings is in principle possible, but verification of the results may be more complicated. Dairy houses with lower animal density may give less convection currents and less uniform distribution of gas concentrations. Several ventilation openings would make a comparison of both methods more difficult as the inlet or outlet function of openings is less defined.

One of the main components in climate control is the ventilation opening. Differences in height between inlet and outlet and size of ventilation openings have been recognized as important aspects in natural ventilation. This thesis adds the shape of the openings as another aspect that has considerable influence on the airflow through openings in natural ventilated buildings. The relationship between pressure difference and airflow through ventilation openings in walls does not only depend on the ratio between horizontal and vertical dimensions of the opening but also on the construction details. Where ventilation openings in natural ventilated buildings were often parts of the buildings shell and as such made by the building contractor, the results presented in this thesis imply that the ventilation openings should be seen as parts of the climate control system. A good quality of these components can be assured best by having these parts supplied by the climate control contractor. Components for natural ventilation systems already supplied by climate control contractors include circular chimneys. In this study it was found that the resistance to airflow through circular chimneys in livestock buildings confirms theory. This implies that theory on fluid dynamics can be used for further optimization of the efficiency of ventilation openings in natural ventilated buildings. Especially current wall openings with little emphasis on aerodynamical design can be improved considerably. In buildings with natural ventilation, where pressure differences are small, it was shown that air flow guiders at entrances of wall openings or chimneys are able to increase maximum airflows with 35% in wall openings and with 25% in the chimney. Pressure gradients over ventilation openings are relatively small under natural ventilation.

Volatilization of ammonia from livestock buildings has reached unacceptable levels in certain areas. The Southern and Eastern parts of the Netherlands, Brittany in France, the Western part of Belgium, Denmark, Catalonia in Spain, the Po valley in Italy and certain parts of Niedersachsen and Nordrhein Westfalen in Germany are areas with high ammonia production (Asman & Jaarsveld, 1992). When the production of ammonia can not be limited within livestock buildings, it can be necessary to remove ammonia from the exhaust air. Available techniques like air scrubbers or bio filtration can not be used in combination with the ventilation openings in use with natural ventilation. These techniques generally require pressure gradients above 30 Pascal, which are well above the average pressure gradients created in natural ventilated buildings. On the other hand air cleaners are seen as an expensive end-of-pipe solution, while additional benefits in terms of improvements of the climate for the animals can be obtained by prevention of the production of ammonia. In the Netherlands a research program is carried out in this field and promising results have been achieved in the fields of nutrition by reduced input of nitrogen and manure removal systems, where manure is stored outside the building in covered silo's. This means that for livestock buildings in areas with excess ammonia emissions, solutions are well under way that can be combined with ventilation openings without fans.

A control algorithm for natural ventilation in pig houses that applies a carbon dioxide balance will have to combine zoological and control characteristics. The algorithm presented in this thesis uses the heat and carbon dioxide production of pigs with a distinct diurnal pattern. The zoological characteristics are essential and must either be included in the software or require manual entry on location. Whatever can be included in the software releases the producer of some data entry, but makes the software more specific to a certain species or category of a species. Suppliers of controllers may prefer uniform software for the sake of simplicity of maintenance and will have to study how to achieve an optimum between minimum numbers of software versions and minimum amount of on-site data entry.

Another aspect of such an algorithm is that while animal data are available in the controller to enable determination of the ventilation rate, these data can also be used for determination of climate setpoints. The setpoint determination is a multidisciplinary task of translating animal data into climate setpoints. It is common practice to leave this to the producer or his adviser. This setpoint determination can be included as a routine in the control algorithm, shifting this task from the human level to a tool at the machine level. A pig producer may appreciate this tool and rely on it, but he can also consider it merely as an advice and overrule it with his own setting.

As the animal data required by the climate control algorithm may also be needed in other processes on the farm, a form of electronic interchange of data on farm level would save some data entry and enables an electronic link between climate control on operational levels and management evaluation on tactical levels.

The climate model presented is a useful tool to tune control algorithms as shown by the results. Tuning of a controller is an aspect that may receive unsufficient attention when left to the stage of installation, what would result in unnecassary quick or slow response of actuators leading to greater deviations from setpoints or extra heating costs and in more severe cases to unstable controllers. Another potential application for this model is the testing of different control algorithms including the development of energy saving strategies for pig houses.

Animal performance is an important criterium in the selection of a ventilation system on a farming enterprise. Historically natural ventilation systems had a poor quality climate control, mostly manual, what hampered animal performance in these systems. This has resulted in natural ventilation systems having a negative image in certain countries. To compare animal performance under natural and mechanical ventilation systems data have been collected from several rooms over prolonged periods. Weaned piglets, being young animals with high climate demands and without the support of their mother or nest facilities have been used for this comparison. Although the complex interactions between health status, hygiene status, climate, nutrition and housing contribute to considerable variations in growth rates between batches of piglets groups within rooms it is clear that growth rates can be equally good in houses with natural ventilation systems as in houses with mechanical ventilation systems. This may look evident, considering that under an equal climate equal performance is expected no matter what driving forces were used to generate this climate. Climates are never constant and difficult to characterize and therefore difficult to compare. This makes it hard to substantiate that the climate in a particular house is better or equal to the climate in another room. Animal performance can be used as a parameter to evaluate climate control, this parameter is indirect but has economic signifance and is therefore generally accepted. The results on growth rates are based on prolonged periods including all seasons but no power failures occured during the comparison of performance. Introduction of natural ventilation systems with adequate control may therefore not be impeded by poor animal performance. Dissemination of these results to extension services, pig producers and manufacturers of climate controllers will contribute to introduction of natural ventilation systems.

Final conclusions

The scope of the study was to implement a climate control technique for pig houses based on natural ventilation. From this study it is clear that successful application of natural ventilation in pig houses is possible with selection of correct ventilation openings, use of a carbon dioxide balance for determination of the ventilation rate and the use of an appropriate control algorithm while having good animal performance.

Natural ventilation in pig houses is possible and results in reduced energy costs for ventilation compared to mechanical ventilation without negative effects on the growth of pigs.

Air flow control in pig houses with natural ventilation is possible, making control of energy costs concentration possible in heated pig houses.

Incorporation of models for animal heat and carbon dioxide production in climate control algorithms is possible and can be combined with determination of setpoints within the climate control algorithm.

The emission of carbon dioxide from fossile fuels from pig houses can be reduced by transformation from mechanical ventilated buildings to natural ventilated buildings.

Recommendations for further research

The application of natural ventilation systems with airflow control can possibly be broadened to livestock species other than pigs. Broilers and turkey houses can be controlled as well in this way. Studies on the production of carbon dioxide from manure in poultry houses (e.g. van Beek & Beeking, 1992) should be analysed including the diurnal production pattern of carbon dioxide, to evaluate the use of a carbon dioxide balance in poultry houses.

Industrial suppliers of climate controllers may prefer to produce multipurpose controllers that can be used in various markets (Doyle, 1986). The use of animal data within controllers would need either specific software for each market segment or require complex software within the controller. On the other hand the use of animal data would facilitate integrated management on livestock enterprises. A possible direction that would combine the wish to produce multi-purpose controllers with the possibility to utilize animal data would be to link climate controllers to a management information system that could run on a personal computer (Van 't Klooster & Lokhorst, 1988). It is suggested to develop and implement a standard communication protocol between process computers and management information systems in the pork industry. Standardization of such a protocol will probably enhance progress in the development of computer aided integrated management in pig husbandry.

Direct measurement of ventilation rates in livestock buildings with natural ventilation can be an interesting alternative for the carbon dioxide balance as the cost of a sensor can probably be lower. It is suggested to develop and test the sensor in a natural ventilated system where the pressure gradient over the section with the sensor is fairly stable and to compare the quantitative results with other methods.

The system for air distribution in a room affects air velocities. Air velocity at animal level plays a role in the heat exchange between animal and its environment. The air velocity and the control over air velocity at animal level has not been part of this study. Study of these aspects can contribute to a further improvement of climate control for pigs and a shift from climate control at room level to pen level or animal level (Berckmans et al., 1992).

Climate control in pig houses has involved heating and ventilation but not cooling as technique to realize an acceptable indoor climate. Interest in full control over the climate in pig houses by cooling is rising in the Dutch pork industry. Most of these cooling techniques are used in mechanical ventilation systems (e.g. earth tube heat exchangers, heat pumps, groundwater heat exchangers). In cases where benefits of cooling are found, the potential for combining natural ventilation and cooling in pig houses should be explored. Techniques developed for greenhouses (e.g. De Jong et al., 1993). can be evaluated on their applicability for livestock housing.

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SUMMARY

SUMMARY

Natural ventilation in pig houses is an old ventilation principle. The increases in productivity and scale have created a demand for automatic systems for climate control in pig houses. Mechanical ventilation systems that control temperatures and ventilation rates are available and have become popular. During the last two decades natural ventilation systems that provide automatic control over temperatures have reached the market. A remaining problem is the automatic control over ventilation rate. Insufficient control over ventilation rate may result in poor air quality or excesssive heating costs. In principle the ventilation rate can be determined by measuring the driving forces for ventilation, pressure and temperature gradients, by measuring the ventilation rate directly or by measuring the results of ventilation. An example of this last technique is developed in this thesis based on a carbon dioxide balance. Animal data are necessary to determine the source term in the carbon dioxide balance.

Natural ventilation systems are only an interesting option for pork producers when no negative effects on animal performance are observed as compared to other ventilation systems. Growth rates of pigs are not lower in natural ventilation systems than in mechanical ventilation systems when the same level of automation is applied. Even with a vulnerable catagory of pigs, weaned piglets, this was found to be the case. Because the ventilation capacity in natural ventilated pig houses is dimensioned for the worst case, hot, windless days, capacity is more than adequate on less extreme days, often resulting in ample ventilation. This will improve air quality, but to reduce the energy costs, control over air flow is desirable when supplementary heating is used.

To optimize the capacity of ventilation openings in natural ventilated pig houses attention should be paid to the airodynamic shape of the openings. Measurements showed that the relation between pressure gradient and ventilation rate through wall openings depend not only on surface and height/width ratios, but also on construction details that influence the flow guidance. In pig houses with natural ventilation, where pressure differences are small, the use of flow guiders can increase the air flow rates through rectangular wall openings with 35% and in roof mounted cylindrical chimneys with 25%. Measurements of the air resistance of these cylindrical chimneys, as used in animal housing, are in agreement with the theoretical results.

The use of a carbon dioxide balance in combination with an on-line sensor to measure the carbon dioxide concentration enables a continuous estimation of the ventilation rate. The number of pigs and their weight and feed intake are used to quantify the daily heat- and carbon dioxide production. The diurnal patterns in the carbon dioxide production must be determined to estimate the carbon dioxide production at a particular moment. The

storage and removal of carbon dioxide are also terms in the equation used to determine the ventilation rate. Tracer gas techniques can be used in pig houses with natural ventilation. Tracer gas measurements correlate well with estimations of ventilation rates made with a carbon dioxide balance.

A reduction in the use of electric energy with 90% can be realized when mechanical ventilation systems in pig houses are replaced by natural ventilation systems. When a similar degree of control over air flow is realized, the use of energy for heating will be equal for both systems. When new pig houses are erected, the savings in energy costs are sufficient to compensate for the higher investment costs of natural ventilation systems with air flow control. The potential for energy savings by changing from mechanical to natural ventilation systems in the Dutch pork industry is estimated to be 560 TJ per annum for finishing operations and to be 290 TJ per annum for breeding and nursery operations.

In commercial pig units climate control requires setpoints in terms of temperatures and air flow rates. Both the desired thermal environment and the desired air flow rate to control air quality are parameters that can be derived by available equations from animal data. A control algorithm is presented that is based on animal data and results are presented to illustrate that the indoor climate could be kept within the desired ranges. The automatic link between animal data and climate control enables a link between climate control and feeding to optimize these two processes. Further research can show whether linking a management information system to both a climate controller and a feeding computer offers benefits in better operational control and better evaluation tools in pig production.

For optimal control of temperature and ventilation rate controllers with proportional gain, integrating and differentiating actions can be used. The process to tune to the correct gain factors and time constants can be time consuming when done on site with emperical rules. Besides a comparison of different values under identical conditions creates practical difficulties. To solve this, a dynamic model was formulated to describe the climate and the control algorithm for a pig house with natural ventilation. After calibration the model can adequately describe both the dynamics and the absolute values of the climate in the house. The model is a useful tool to tune the control algorithm for a particular building and makes a quick comparison between different tunings under identical conditions possible.

It is expected that pig houses will have to meet strict regulations concerning environmental pollution. In the Netherlands the emission of ammonia will have to be reduced. In situations where room air has to be treated by air scrubbers or biofilters, before it can be released, pressure gradients are required that can not or insufficiently be generated in houses with natural ventilation systems. Currently research on reduction of ammonia emission is primarely directed to a reduction in ammonia production by reduced input of nitrogen and by systems with frequent manure removal to covered storage facilities outside the house. Once these techniques become available, natural ventilation systems can also be applied in animal houses that have to comply with strict emission legislation.

Samenvatting

SAMENVATTING

Natuurlijke ventilatie wordt reeds lang in varkensstallen toegepast, maar is in de Nederlandse varkenshouderij de laatste decennia grotendeels vervangen door mechanische ventilatie. De behoefte aan automatische systemen, die voortdurend het klimaat aanpassen, is sterk toegenomen. Voor natuurlijke ventilatie zijn hiervoor weinig systemen ontwikkeld. Wel is reeds enige jaren een temperatuurregeling beschikbaar, maar een ventilatiehoeveelheidsregeling ontbreekt nog steeds voor stallen met natuurlijke ventilatie. De ventilatiehoeveelheid zou bepaald kunnen worden door de drijvende krachten te meten en daaruit de ventilatie te berekenen, door de ventilatiehoeveelheid zelf direct te meten of door de gevolgen van de ventilatie te meten. Deze laatste mogelijkheid is in dit proefschift uitgewerkt in de vorm van een kooldioxyde balans, waarbij diergegevens nodig zijn om de produktieterm te bepalen.

Natuurlijke ventilatie systemen zijn voor varkenshouders slechts interessant indien dit geen negatieve gevolgen voor de produktieresultaten van de dieren heeft. De groei van varkens hoeft bij gelijke graad van automatisering in natuurlijk geventileerde stallen niet lager te liggen dan in mechanisch geventileerde stallen. Zelfs bij een kwetsbare diercatagorie als gespeende biggen bleek dit het geval te zijn. Omdat in natuurlijk geventileerde stallen de ventilatiecapaciteit gedimensioneerd wordt op warm, windstil weer, is er bij minder extreem weer een forse overcapaciteit en wordt er veelal meer geventileerd dan nodig is. Dit kan gunstig zijn voor de luchtkwaliteit maar ter vermindering van de energiekosten is beperking van de ventilatie hoeveelheid gewenst als de gewenste minimum temperatuur onderschreden wordt danwel moet worden bijverwarmd.

Om de capaciteit van ventilatie openingen bij natuurlijk geventileerde stallen optimaal te benutten is aandacht voor de stroomlijning van de openingen zinvol. Het verband tussen drukverschil en luchtopbrengst door ventilatieopeningen in wanden van stallen blijkt uit verrichtte metingen niet alleen af te hangen van oppervlak en verhouding van hoogte en breedte van de openingen maar ook van de wijze van constructie, waarbij de luchtgeleiding een belangrijke rol speelt. In stallen met natuurlijke ventilatie, waar de drukverschillen klein zijn, is toepassing van instroomranden om de luchtstroom te geleiden zeer zinvol. In wandopeningen verhoogt dit de maximale luchtopbrengst met 35% en in dakkokers met 25%. Metingen aan de luchtweerstand van dakkokers, zoals in veehouderij gebouwen toegepast, zijn in overeenstemming met theoretische grondslagen.

Het gebruik van een kooldioxydebalans in combinatie met een meting van de kooldioxydeconcentratie maakt continue schatting van de ventilatiehoeveelheid in varkensstallen mogelijk. Op grond van aantal dieren, hun

gewicht en hun voeropname kan de warmte- en kooldioxyde produktie in een etmaal worden geschat. De schommelingen binnen etmalen in de produktie van kooldioxyde moeten gebruikt worden voor het schatten van de kooldioxydeproduktie op een bepaald moment. De ventilatiehoeveelheid in varkensstallen kan worden bepaald uit deze produktie en uit het concentratieverloop in de stal. Het gebruik van tracergassen in varkensstallen voor het meten van de ventilatiehoeveelheid is een techniek die toegepast kan worden. Deze metingen geven een goede correlatie met de schattingen van de ventilatie hoeveelheden met behulp van de kooldioxydebalans.

Een vermindering van de electriciteitskosten met meer dan 90% is haalbaar, door over te schakelen van mechanische naar natuurlijke ventilatie. Deze kostenbesparing is voldoende om onder Nederlandse omstandigheden bij nieuwbouw de extra investeringskosten te compenseren. Voor Nederland kan de maximale energiebesparing die bereikt kan worden door over te schakelen van mechanische naar natuurlijke ventilatie, worden geschat op 560 TJ per jaar in de vleesvarkenshouderij en op 290 TJ per jaar in de zeugenhouderij.

Klimaatregeling gebeurt in de praktijk door de gewenste temperatuur en ventilatiehoeveelheid in te stellen. Zowel het gewenste thermische klimaat als de gewenste ventilatiehoeveelheid voor regeling van de luchtkwaliteit zijn gegevens die volgens bekende rekenregels terug te voeren zijn op de aanwezige dieren. Met het hier gepresenteerde regelalgoritme blijkt het inderdaad mogelijk het klimaat te regelen binnen de gewenste waarden. De koppeling tussen diergegevens en de klimaatregeling zoals in dit regelalgoritme maakt het in principe mogelijk om de processen klimaatregelen en voerverstrekken met elkaar te verbinden en op elkaar af te stemmen. Een technische mogelijkheid voor een dergelijke verbinding is het aansluiten van beide procesregelaars op een personal computer met een managementinformatiesysteem. Hierdoor zou een gezamenlijke optimalisatie van beide processen kunnen worden gecombineerd met een evaluatie van de dierproduktie die gebaseerd is op ondermeer klimaat- en voergegevens.

Als voor een optimale regeling van de temperatuur en ventilatiehoeveelheid gebruik wordt gemaakt van zowel proportionele, als integrerende en differentierende regelaars, is het empirisch instellen van de versterkingsfactoren en tijdsconstanten een proces, waarbij het vergelijken van verschillende waarden erg tijdrovend kan zijn. Bovendien is het vergelijken van waarden onder dezelfde condities praktisch moeilijk uitvoerbaar. Er is daarom een dynamisch model opgesteld dat voor een stal zowel het klimaat als de regeling ervan beschrijft. Na kalibratie van het model bleek het model het werkelijke klimaat zowel in dynamiek als het absolute niveau adequaat te kunnen beschrijven. Met dit model bleek het mogelijk om alternatieve waarden voor regelaars snel en onder identieke condities te vergelijken.

In de toekomst zullen zwaardere eisen worden gesteld aan de milieubelasting vanuit varkensstallen. De uitstoot van ammoniak zal in Nederland moeten verminderen. Natuurlijke ventilatie systemen zullen niet kunnen worden toegepast op plaatsen waar de stallucht nabehandeld moet worden met een luchtwasser of biobed, voordat deze lucht geloosd mag worden op de buitenlucht. De benodigde drukverschillen voor deze nabehandelingen kunnen niet of in onvoldoende mate middels natuurlijke ventilatie gerealiseerd worden. Omdat oplossingen voor de vermindering van de ammoniak uitstoot vooral gezocht worden in vermindering van de produktie van ammoniak door een lagere aanvoer van mineralen en een snelle afvoer van mest naar een gesloten opslagplaats, is te verwachten dat natuurlijke ventilatiesystemen ook in stallen die aan strenge emissie eisen moeten voldoen, toegepast kunnen worden.

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Curriculum Vitae

Cornelis Everardus van 't Klooster was born on September 23rd 1956 in Haule, the Netherlands. Upon completing secondary school at the "Rijksscholengemeenschap Ooststellingwerf" in Oosterwolde in 1974 he studied mathematics and physics at State University Groningen. After passing the "propaedeutisch examen" he started to study Agricultural Engineering in 1975 at Wageningen Agricultural University. In 1978-1979 he worked at the Center for Agricultural Research in Surinam as part of his study. He graduated in 1981 with agricultural machinery and farm structures as main subjects and information science as minor subject. From 1981 till 1984 he was employed by Eindhoven University of Technology and assigned as lecturer in the Department of Agricultural Engineering to the University of Zambia in Lusaka. From 1984 till 1986 he worked for Wageningen Agricultural University as lecturer both in Zambia and in Wageningen. In 1986 he joined the Research Institute for Pig Husbandry in Rosmalen as researcher climate control. His research on natural ventilation is described in this thesis. In 1994 he started in his current position as head of the Department of Livestock Engineering at the DLO-Institute for Agricultural and Environmental Engineering in Wageningen.