Identification of Risk Factors for Sub-Optimal Housing Conditions in Australian Piggeries:

Part 3. Environmental Parameters

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Abstract. *Between autumn 1997 and autumn 1999, we measured ventilation rates (using a CO_2 balance method), air temperatures, and relative humidity (using self-contained dataloggers with built-in sensors) in 160 pig housing facilities in Queensland, South Australia, Victoria, and Western Australia, in each case over a 60 h period. In some buildings, the internal air velocities above the animals were also recorded. While the monitoring instruments were being set up, a detailed questionnaire was used to collect data on major housing features and management factors. This information was statistically analyzed to quantify the effects of housing and management factors on the resulting environment conditions using a multifactorial analysis. The overall mean air temperature, relative humidity, internal air velocity, and ventilation rate were 20.3°C, 58.9%, 0.12 m s^{-1}, and 663.9 m^3 h^{-1} 500 kg^{-1} live weight, respectively, across all buildings. Internal building temperature and humidity were affected statistically by the type of insulation material used, the classification of buildings, and external climatic conditions. Ventilation rates were primarily affected by the type of ventilation system used, height (size) of ventilation openings, stocking density (kg m^{-3}), and length, width, and height of buildings. These findings should aid the development of strategies for the industry to improve environmental control in piggery buildings.*

Keywords. *Environmental survey, Farm building, Humidity, Risk factors, Statistical models, Temperature, Ventilation.*

The concentrations of airborne pollutants, the production efficiency, and the welfare of pigs are influenced by the environmental conditions of housing provided (Banhazi et al., 2008b; Gates et al., 1991). The environmental conditions in piggery buildings are controlled mainly by the engineering features of the building (insulation material, heating and cooling equipment used) and the ventilation system installed. The climate in piggery buildings need to be managed to ensure that pollutant concentrations are minimized and the thermal environment is optimized in order to maximize production efficiency. Ventilation systems installed in piggery buildings are designed to achieve these aims. In theory, maximum ventilation rates are used mainly in hot weather for reducing heat loading on pigs by increasing ventilation air velocity (Seedorf et al., 1998a,

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1998b). Minimum ventilation rates are used in cold weather to maintain acceptable air quality and at the same time minimize heat loss from piggery buildings (Seedorf et al., 1998a).

The environmental control systems of piggery buildings are designed to ensure that a balance can be maintained between the heat produced by the animals and the heat lost via the building structure and ventilation. Modern piggery buildings are designed to keep the animals in their optimal thermal environment, or "thermoneutral zone" (TNZ), where they can convert feed to lean tissue efficiently (Lopez et al., 1991). The TNZ is situated between the upper (UCT) and the lower critical temperatures (LCT) (Brown-Brandl et al., 2004; Gates et al., 1991). Although the thermal environment of intensively housed pigs is influenced mainly by air temperature, humidity, and air velocity (Black et al., 1999; Boon, 1978, 1982; Riskowski and Bundy, 1990), other factors such as the age of the pigs, type of flooring, stocking rate, skin wetness, and nutrition also have marked effects on how individual animals are affected by the thermal conditions in the building (Botermans and Andersson, 1995; Geers et al., 1989; Jones and Nicol, 1998). This subjective thermal comfort is also called the "perceived" thermal environment (Gates et al., 1991) and therefore can be quite different for different pigs, depending on the previously mentioned factors.

A previous study conducted in Australia indicated that the environmental conditions in many pig housing facilities are often outside the optimal range (Buddle et al., 1994). These results indicate a lack of adequate environmental control in Australian piggery buildings, a problem that needs to be addressed if production efficiency is to be maximized (Geers et al., 1989). No previous studies have attempted to statistically model, and therefore explain, the important factors affecting environmental conditions in piggery buildings. Therefore, we implemented a comprehensive study in piggery buildings to determine the key design and management factors that statistically affect internal conditions. The statistical nature of the study was important, as it was hoped that such an approach would enable us to identify significant factors that have dominant influence on these variables under field conditions, as opposed to the abstract relationships often described by numerical models. This study had two major aims. First, it aimed to survey actual ventilation rates in order to use the measurements obtained to calculate air pollutant emission rates, as was done in previous studies (Seedorf et al., 1998a). The second aim was to identify the key piggery design and management factors that statistically affect ventilation rates, temperature, and humidity inside piggery buildings because we expected that the models developed would identify practical ways of improving environmental control in commercial piggery buildings.

Materials and Methods

Details of the study design, study buildings, and methodology used for analysis have been published (Banhazi et al., 2008b; Banhazi et al., 2008c) as part of this series, and therefore only the specific methods used for temperature, humidity, and ventilation measurements are given here. In brief, 160 piggery buildings from 40 farms were included in the study, and the buildings were selected to represent a range of typical construction methods used in Australia (Banhazi et al., 2008b). Data were recorded over a 60 h period (in both winter and summer), and a data collection form (detailed in table 3 in the first part of this series) was developed to collect information relating to building engineering and management (Banhazi et al., 2008b).

Temperature and Humidity Measurements

Self-contained, battery-operated dataloggers with built-in sensors (Tinytalk-2, Hastings Dataloggers Pty. Ltd., Port Macquarie, Australia) were used to measure temperature and relative humidity both inside and outside of all buildings. These sensors came with factory calibration. The range of the temperature sensors was -45 °C to +75 °C, with a documented accuracy of ±0.5 °C at 25 °C. The humidity sensors had a range of 0% to 100%, with a documented accuracy of ±3% at 25 °C. The sensors were placed as close to pig level as practicable without allowing the pigs to interfere with the instruments. In most buildings, the dataloggers were attached by wire cable to the ceiling or a beam and were lowered to pig level (approximately 1.1 to 1.3 m) above a selected pen.

Air Velocity Measurement

In some buildings, the internal air velocity was measured with a hot-wire anemometer (Alnor Instruments, Shoreview, Minn.). The instrument's extendable probe was attached by a wire cable to the ceiling or beam and was lowered into an appropriate position above a pen. The built-in datalogger was used to record air velocity every 7.5 min over a 60 h monitoring period. The instrument came with the factory calibration and appeared to be reliable at the beginning of the survey. However, because of technical difficulties associated with dust build-up on the measuring wire, the instrument was decommissioned and removed from the measurement kit. Frequent visual observation of the sensor wire and the assessment of the obviously incorrect data (for example, initial readings for a few hours and then a drop to almost zero readings) convinced us to remove the equipment from the instrumentation kit of the study. Air velocity results presented in table 2 are based on a small dataset obtained at the early stage of the study, when the measurement instrumentation was still performing adequately.

Ventilation Estimation

The concentration of CO_2 was recorded continuously inside and outside the buildings over periods of 60 h using a multi-gas monitoring (MGM) machine developed in-house. An infrared sensor (GMM12, Vaisala Oy, Helsinki, Finland) was used to detect CO_2 concentrations, as described previously (Banhazi et al., 2008c). Ventilation rates were calculated by a CO_2 balance method. Commercially available software (ANIPRO, developed from the early version of the Stalkl program) was used to compute the calculations required, using external and internal CO_2 concentrations (Ouwerkerk and Pedersen, 1994). This technique has a reported accuracy of ±15% and can be applied in both naturally and mechanically ventilated buildings (Ouwerkerk and Pedersen, 1994; Seedorf et al., 1998a). From the ventilation rate (m^3 h^{-1}), emission rates were also calculated for individual buildings by multiplying the ventilation flow rate by the measured internal concentration of each pollutant and were expressed per livestock unit (LU, 500 kg live weight). Total ventilation airflow rates (m^3 h^{-1}) were calculated over a 60 h period for each piggery building and also expressed per LU.

Data Analysis

Data were forwarded to a central location for storage and analysis, which is described in detail in a companion article (Banhazi et al., 2008b). Unlike air pollutant data (Banhazi et al., 2008c), temperature and humidity data were normally distributed, and therefore log-transformation was not necessary. A general linear model procedure was used to analyze the data (SAS, 1989) to ensure that the unbalanced nature of the data obtained under field conditions was adequately dealt with. The models developed were based on a large number of fixed effects and covariates and their first-order interactions, as detailed in a companion article (Banhazi et al., 2008b). The results of these analyses are presented as least squares means (±standard errors) of fixed effects. Data related to total ventilation airflow rates were also analyzed using a general linear model procedure (SAS, 1989) but only after the raw data had been log-transformed. The results from this analysis are based on the medians (back-transformed means ±confidence intervals) of the fixed effects. Because of the limited number of observations of air velocity (12 buildings), a model to explain variation in air velocity could not be developed.

Results

Summaries of the raw means of internal and external air temperatures and relative humidity by building type (building classification) and season are presented in table 1. Mean temperature values were calculated from the mean building averages.

In winter, mean air temperatures of 17.5°C and 17.9°C were measured in grower and finisher facilities, respectively. The mean summer air temperatures for grower and finisher pigs were 22.8°C and 22.9°C, respectively. Weaner buildings had higher temperatures: 20.0°C in winter and 23.8°C in summer. Standard deviations based on building averages for weaner and grower facilities were similar. All piggery buildings had low relative humidity measurements in both seasons. In table 2, the mean values of the estimated ventilation rates and measured internal air velocities are shown.

In some study buildings, data were not collected successfully due to problems related to project logistics, instrumentation, or personnel. The details of the analyses undertaken are summarized in table 3. Almost 80% of the variation was explained by the ventilation and air temperature models, which indicated a highly relevant model (table 3). For the relative humidity, lower model R^2 values were achieved (table 3). Low numbers of

Table 1. Mean internal and external air temperature (Temp., °C) and relative humidity (RH, %) values in different piggery buildings, based on measurements over 60 h (*N* = number of buildings, SD = standard deviation).

	Internal		External	
Building Type	Temp. (*N*) SD	RH (*N*) SD	Temp. (*N*) SD	RH (*N*) SD
Grower				
Winter	17.5 (20) 3.4	63.5 (18) 11.5	12.8 (20) 4.4	73.6 (17) 9.7
Summer	22.8 (13) 2.9	51.9 (16) 12.9	20.5 (13) 3.5	58.7 (15) 16.4
Finisher				
Winter	17.9 (12) 3.8	56.1 (12) 17.4	14.0 (11) 4.5	66.8 (12) 20.9
Summer	22.9 (15) 2.9	49.8 (13) 18.8	20.4 (14) 3.5	50.8 (12) 18.8
Deep-bedded shelters				
Winter	16.7 (8) 3.7	66.0 (7) 6.5	13.8 (8) 3.8	72.6 (7) 16.8
Summer	22.4 (3) 1.6	48.2 (3) 17.2	20.3 (3) 2.9	54.5 (3) 8.3
Dry sow				
Winter	15.7 (9) 2.7	67.1 (10) 10.0	11.9 (10) 3.3	75.5 (10) 9.0
Summer	21.3 (9) 2.9	61.5 (12) 14.0	20.9 (10) 4.0	65.2 (12) 12.3
Farrowing				
Winter	19.2 (16) 3.5	60.7 (16) 8.2	13.4 (17) 3.8	71.0 (16) 9.0
Summer	23.9 (12) 2.1	55.7 (13) 12.9	21.5 (12) 4.1	63.4 (13) 11.1
Weaner				
Winter	20.0 (19) 3.8	60.1 (17) 10.4	12.4 (18) 3.3	79.9 (17) 13.0
Summer	23.8 (12) 3.0	63.2 (12) 9.1	19.3 (12) 4.4	72.8 (12) 8.6
All buildings	20.3 (148) 4.1	58.9 (149) 13.3	16.2 (148) 5.3	68.1 (146) 15.4

Table 2. Descriptive statistics of environmental factors measured in different piggery buildings.

Ventilation Measure	Mean	Median	No. of Buildings	Min.	Max.
Total ventilation airflow (m^3 h^{-1})	27,610.9	12,216.0	109	212.0	378,103.0
Ventilation airflow (m^3 h^{-1}) per livestock unit[a]	663.9	479.0	109	37.0	5704.0
Air velocity (m s^{-1})	0.12	0.08	12	0.05	0.39

[a] Livestock unit (LU) = 500 kg live weight.

Table 3. General linear models developed for ventilation airflow (m^3 h^{-1}) at the 99% confidence level and air temperature and relative humidity at the 99.9% confidence level.

	Total Ventilation Airflow	Air Temperature	Relative Humidity
Model degrees of freedom	9	8	4
Corrected total degrees of freedom	108	144	141
Total sum of sum of squares	218.279	2441.63	25992.08
Model R^2 (%)	79.6	77.8	60.9

Table 4. Significance of effects associated with internal air temperature, relative humidity, and ventilation airflow.[a]

	Ventilation Airflow (m^3 h^{-1})	Air Temperature (°C)	Relative Humidity (%)
External air temperature	--	***	--
External relative humidity	--	--	***
Wall insulation type	ns	***	***
Roof insulation type	*	ns	**
Type of building	ns	***	ns
Stocking density (kg m^{-3})	**	**	ns
Wall ventilation inlet height	**	*	*
Ridge vent height	ns	**	**
Building age	ns	**	*
Ventilation type	**	ns	ns
Ridge ventilation control type	*	**	*
Building width	**	ns	ns
Building length	**	ns	ns
Building height	**	ns	*
Building height × ventilation type	**	ns	ns
Stocking density × ridge vent control	*	**	ns
Building age × wall insulation type	ns	**	*
Ridge vent height × wall insulation type	ns	ns	**

[a] Effects influencing at least one of the variables at the 99% significance level, or higher, are shown: * = $P < 0.05$; ** = $P < 0.01$; *** = $P < 0.001$; and ns = non-significant, not included in model.

degrees of freedom were used in the models (compared to all available degrees of freedom), which indicate the robustness of the models developed (table 3).

The outcomes of the analyses of effects are summarized in table 4, and key results of the analysis of individual variables are shown in table 5 and figures 1 to 3.

For total ventilation airflow, the main effects identified were ventilation type, stocking density (kg pig m^{-3} airspace), height of wall ventilation inlet, and building width, length, and height (table 3) at the 99% significance level. The important main effects ($P < 0.001$) identified with the air temperature model were type/classification of building, external

Table 5. Effects of different covariates on total ventilation airflow rates (m^3 h^{-1}), internal air temperature (°C) and relative humidity (%).

Variable	Covariate	Interaction	Slope
Ventilation airflow rate	Building height (m)	Building type[a]	Positive
Ventilation airflow rate	Building width (m)	ns[b]	Positive
Ventilation airflow rate	Building length (m)	ns	Positive
Ventilation airflow rate	Height of vent openings (air inlets)	ns	Positive
Ventilation airflow rate	Stocking density (kg pigs m^{-3})	ns	Negative
Internal air temperature	External air temperature	ns	Positive
Internal relative humidity	External relative humidity	ns	Positive

[a] Slope associated with deep-bedded shelters (DBS) were significantly different from other buildings, and the slopes associated with other building types were not significantly different from zero.

[b] ns = no significant interaction was found.

air temperature, and wall insulation type. For relative humidity inside piggery buildings, external humidity and wall insulation type were identified as highly important ($P < 0.001$).

The model developed for ventilation airflow indicated that with increasing stocking density (kg pig m^{-3}) the total ventilation airflow rate decreased (table 4). All other main effects (building height, width and length, as well as size of ventilation opening) were positively associated with total ventilation airflow rate. In the air temperature model, external temperature was strongly and positively associated with internal temperatures ($R^2 = 0.67$), and external humidity also demonstrated a strong positive relationship ($R^2 = 0.55$) with internal relative humidity (table 4).

In addition to the dominant effect of external temperature, the effect of building type on internal temperatures was highly significant (fig. 1). Dry sow buildings had the lowest mean air temperature (19.7°C), whereas farrowing buildings (21.6°C), deep-bedded shelters (DBS; 20.2°C), and finisher buildings (20.9°C) were maintained at similar mean temperatures. The highest mean air temperatures were maintained in weaner buildings (23.1°C).

The air temperature and relative humidity models revealed that wall insulation type strongly influenced both air temperature (fig. 2) and relative humidity in piggery buildings (fig. 3). Buildings containing asbestos sheet wall insulation had a mean air

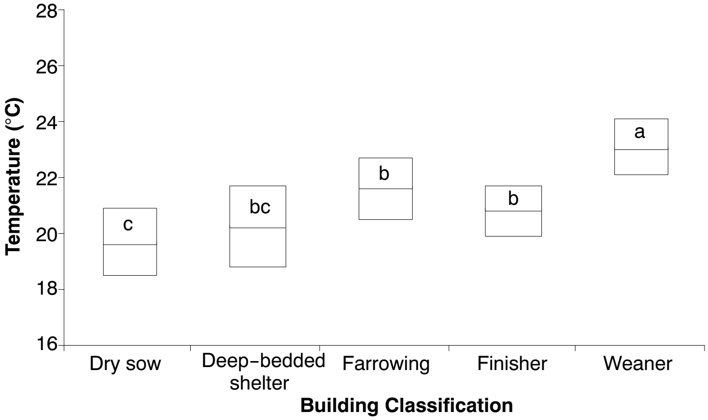

Figure 1. Effects of building classification on air temperature (°C) in Australian piggery buildings (least squares means with standard errors). Different letters indicate significant differences.

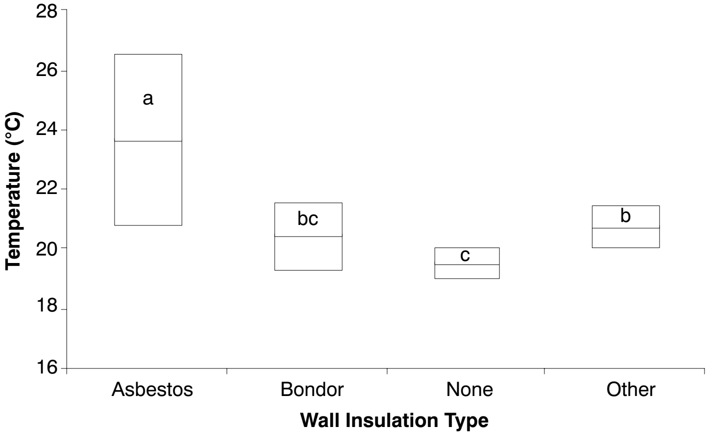

Figure 2. Effects of wall insulation type on air temperature (˚C) in Australian piggery buildings (least squares means with standard errors). Different letters indicate significant differences.

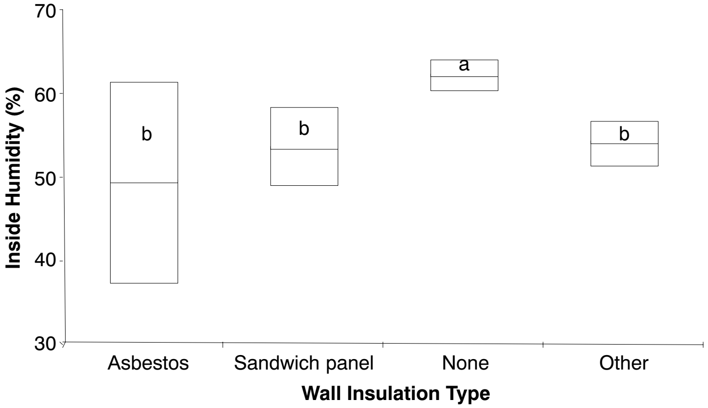

Figure 3. Effect of wall insulation type on relative humidity (%) in Australian piggery buildings (least squares means with standard error). Different letters indicate significant differences.

temperature significantly higher than those containing any other insulation material or no insulation (fig. 2).

Asbestos-lined buildings also had the lowest mean humidity, although the humidity results were not significantly different in the other three building categories (fig. 3). Buildings without insulation had significantly lower mean air temperature (fig. 2) and significantly higher mean relative humidity (fig. 3) than all types of buildings with insulation.

Discussion

Methodology

The method of estimating the ventilation rate for each building by using the CO_2 balance and the ANIPRO program was simple and practical because the commercially available software made emission calculation a relatively simple process. The CO_2

balance method was selected for measuring ventilation rates in the study buildings because the accuracy of estimation of ventilation rate using this method is ±15% (Ouwerkerk and Pedersen, 1994; Seedorf et al., 1998a). The hot-wired anemometer proved to be unworkable as a continuous monitoring instrument in piggery buildings because the high sensitivity of the instrumentation meant that the dust deposited on the measuring wire rendered the instrumentation unusable within a relatively short period of time. In contrast, the self-contained temperature and humidity dataloggers proved to be useful and reliable instruments.

Mean Values

The data collected support previous claims that Australian buildings are loosely controlled thermally (Buddle et al., 1994) because of their open design and high ventilation rates. In terms of absolute throughput, Australian buildings are most probably over-ventilated, especially when compared with European recommendations (Seedorf et al., 1998a). However, high ventilation rates are required to produce air velocities, which could have some cooling effect during times of high air temperatures, especially when the pig's skin is wet and evaporation could occur.

Important Factors Affecting Ventilation Rates

As part of this research, we identified several key factors affecting total ventilation airflow rates inside piggery buildings. A positive relationship between increasing building width, height, and length and total ventilation airflow rate was demonstrated, and the model predicted that larger buildings have greater air throughputs. It is evident from the results (table 2) that, on average, relatively low air velocities (0. 12 m s^{-1}) are maintained in the naturally ventilated piggery buildings typically used in Australia. Therefore, the size of the building will have a large influence on total ventilation airflow, given the limited ability of naturally ventilated buildings to drastically increase and maintain high air velocities over a long period of time.

The vertical height (or size) of ventilation openings also significantly affected total ventilation airflow rates. The vertical height (size) of the openings essentially refers to ventilation inlet size; in the study population (90% of buildings were naturally ventilated), the height of the ventilation opening equated to inlet size. It is easy to understand why increased ventilation inlet size would result in increased airflow in Australian piggeries: the larger the inlet, the greater the volume of incoming air and hence the greater the ventilation airflow rate.

The effect of stocking density on ventilation rates (table 5) was difficult to explain. However, the highest stocking densities (kg pig m^{-3} airspace) were encountered mainly in weaner and farrowing buildings (data not shown). These buildings use reduced ventilation rates owing to the higher thermal requirements of these animals. Therefore, a reduction was observed in ventilation rates in relation to the increased stocking density in these buildings.

Interestingly, seasonal effects on total ventilation airflow rates were not identified (data not shown), and high ventilation rates in winter are potentially compromising the thermal control capacities of piggery buildings. The high ventilation rates also resulted in high emission rates (Banhazi et al., 2008a), despite the fact that the concentrations of airborne pollutants are usually lower in Australian buildings than in European piggeries (Banhazi et al., 2008c).

Important Factors Affecting Air Temperature and Relative Humidity

The models identified the highly significant factors influencing air temperature and relative humidity inside piggery buildings. External temperature accounted for 67% of the variation in internal temperature, indicating that on average only 33% of the variation in temperatures can be controlled by manipulating the engineering features or the management of naturally ventilated piggery buildings. This is a very significant finding of the study, as it quantifies the limited temperature modification capacity of naturally ventilated buildings typically constructed in Australia. However, building type (i.e., weaner, grower/finisher, dry sow, farrowing, or DBS) and wall insulation type (asbestos, sandwich panel, none, and other) accounted for an additional 11% of the variation. This indicated that certain building engineering designs characteristically used in piggery buildings do influence air temperature variation, and therefore these features can be successfully used to exert some control over variation in building air temperatures. In the model developed at the 99.9% significance level, all these highly significant effects accounted for approximately 78% of the variation in internal temperature (table 5). External relative humidity accounted for 55% of the variation in internal relative humidity. In addition, wall insulation type accounted for approximately 6% of the variation in relative humidity, indicating that certain insulation materials used in particular piggery buildings would influence relative humidity. These highly significant effects ($P < 0.001$) together accounted for approximately 61% of the variation in the relative humidity model (table 5). A greater amount of variation was explained in air temperature when compared to relative humidity; indicating that it is easier to control air temperature than relative humidity levels.

Weaner buildings were kept at higher air temperatures, whereas dry sow buildings had significantly lower mean temperatures than all other buildings. DBS and farrowing and grower/finisher buildings were kept at similar temperatures, although temperatures in the farrowing buildings tended to be higher than in either DBS or grower/finisher buildings. This was expected, as farrowing buildings need to be maintained at higher temperatures to maximize the survival of small piglets. However, to avoid interference with the feed intake and milking capacity of lactating sows (Lorschy et al., 1993), these buildings cannot be kept at temperatures as high as those in weaner buildings. Humidity was not affected by building classification (table 3).

The suggested effects of wall insulation type on air temperature followed expected patterns. These results suggest that buildings with asbestos sheet insulation experience the highest mean temperatures, which would indeed be the case, because asbestos insulation is found almost exclusively in older weaner buildings and is rarely used in modern piggery buildings (fig. 2). As demonstrated in this study, weaner buildings are generally kept at higher temperatures than other types of buildings (fig. 1). Sandwich-panel buildings (Bondor) and buildings with other types of insulation (such as spray-on polystyrene) maintained similar temperatures, and buildings with no insulation had the lowest mean temperatures (fig. 2). Relative humidity levels mirrored temperature effects in relation to the different wall insulation types, as expected (fig. 3). Uninsulated buildings had the highest relative humidity, whereas insulated buildings had lower humidities. Differences between insulated building categories were not significant in this instance (fig. 3). High humidity levels have also typically been reported in previous studies in relation to uninsulated buildings (Botermans and Andersson, 1995).

This study supported expectations, and the main factors identified were anticipated to influence environmental quality in piggery buildings. However, the quantification of the influence of these factors is an improvement over previous studies and will be an important step toward the practical enhancement of environmental control in piggery buildings. It is obvious from the results (table 4) that temperature variations are poorly controlled in Australian piggery buildings as a result of the "open" shed design typically favored in these predominantly naturally ventilated buildings. However, it has been documented that reduction of temperature variations in piggery buildings can deliver important health and production benefits (Corcuera et al., 2002; Madec et al., 1998). Therefore, it would be valuable to quantify the effect of temperature variations on pig production and welfare under Australian conditions in order to develop more specific management guidelines and to quantify the benefits associated with improved environmental control. When such information becomes available, it will be possible to weigh the costs associated with management and building construction improvements against the likely production efficiency increases and welfare improvements expected from enhanced environmental control. This further highlights the importance of continuous monitoring of livestock production processes and the development of real-time decision-making tools, which will allow producers to implement management changes while taking into consideration the likely economical consequences of such decisions (Banhazi et al., 2007; Gates and Banhazi, 2002). Current developments pursued in Australia are aimed at achieving this via the implementation of precision livestock farming techniques (Banhazi et al., 2003).

Future Options for Environmental Control

An important consideration when controlling ventilation rates is the potential effect on emission rates (Banhazi et al., 2008a). Increasing ventilation rates are likely to increase emission rates, creating additional environmental concerns (Seedorf et al., 1998a). However, routinely and cost-effectively measuring the concentrations and emissions of airborne pollutants is technically not feasible at present (Seedorf et al., 1998a). Therefore, the design of advanced controllers containing appropriate models for total environmental quality could be used to optimize ventilation, maintain an ideal thermal environment, and minimize the emission of airborne pollutants. In the process of formulating control decisions, these advanced controllers could take into account the real-time output of models that predict the concentrations and emissions of airborne pollutants. Such systems would not require complicated and costly pollutant sensors and could potentially readjust simultaneously the thermal and air quality environments to create a building environment that would maximize production efficiency and therefore financial return. Models developed as part of this study could be used to achive these aims.

Conclusion

Models were developed to explain variations in internal air temperature and relative humidity. The models delivered a number of important results. Building type, external environment, and insulation were proven to have highly significant effects on relative humidity and air temperature. However, other factors, such as building age, stocking density, and size and control of ventilation systems also had significant effects on the humidity and air temperatures recorded in different piggery buildings. Importantly, the models confirmed that the external environment has a dominant influence on internal temperature ($R^2 = 0.67$) and relative humidity ($R^2 = 0.55$) in Australian piggery buildings.

Building size (i.e., building height, length, and width) had an important effect on ventilation airflow rates in piggery buildings. However, clear-cut advice on ideal ventilation rates to achieve optimal environmental quality in piggery buildings cannot be given on the basis of the results of this study. To begin with, ventilation rates cannot be limited drastically, as manipulation of ventilation airflow is currently the only device (limited though it might be) available to producers to control the thermal environment in naturally ventilated buildings. In addition, ventilation airflow throughput does not equate with ventilation quality. Sometimes, a well-directed but lower ventilation airflow will serve the needs of livestock better than an uncontrolled, high ventilation throughput. Increasing the size of the air inlets increases ventilation airflow in naturally ventilated buildings, but as mentioned previously, this does not guarantee the quality of ventilation.

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References

Banhazi, T., J. L. Black, and M. Durack. 2003. Australian precision livestock farming workshops. In *Proc. Joint Conference of ECPA - ECPLF*, 675-684. A. Werner and A. Jarfe, eds. Berlin, Germany. Wageningen, The Netherlands: Wageningen Academic.

Banhazi, T., M. Dunn, P. Cook, J. Black, M. Durack, and I. Johnnson. 2007. Development of precision livestock farming (PLF) technologies for the Australian pig industry. In *Proc. 3rd European Precision Livestock Farming Conference*, 219-228. S. Cox, ed. Skiathos, Greece. Wageningen, The Netherlands: Wageningen Press.

Banhazi, T. M., D. L. Rutley, and W. S. Pitchford. 2008a. Identification of risk factors for sub-optimal housing conditions in Australian piggeries: Part 4. Emission factors and study recommendations. *J. Agric. Safety Health* 14(1): 53-69.

Banhazi, T. M., J. Seedorf, D. L. Rutley, and W. S. Pitchford. 2008b. Identification of risk factors for sub-optimal housing conditions in Australian piggeries: Part 1. Study justification and design. *J. Agric. Safety Health* 14(1): 5-20.

Banhazi, T. M., J. Seedorf, D. L. Rutley, and W. S. Pitchford. 2008c. Identification of risk factors for sub-optimal housing conditions in Australian piggeries: Part 2. Airborne pollutants. *J. Agric. Safety Health* 14(1): 21-39.

Black, J. L., H. J. Bray, and L. R. Giles. 1999. The thermal and infectious environment. In *A Quantitative Biology of the Pig*, 71-97. Kyriazakis, ed. Wallingford, U.K.: CABI Publishing.

Boon, C. R. 1978. Airflow patterns and temperature distribution in an experimental piggery. *J. Agric. Eng. Res.* 23(2): 129-139.

Boon, C. R. 1982. The effect of air speed changes on the group postural behaviour of pigs. *J. Agric. Eng. Res.* 27(1): 71-79.

Botermans, J., and M. Andersson. 1995. Growing-finishing pigs in an uninsulated house: 2. Pen function and thermal comfort. *Swedish J. Agric. Res.* 25(2): 83-92.

Brown-Brandl, T. M., J. A. Nienaber, H. Xin, and R. S. Gates. 2004. A literature review of swine heat production. *Trans. ASAE* 47(1): 259-270.

Buddle, J. R., A. R. Mercy, and S. Z. Skirrow. 1994. The inability of pig sheds to provide ideal environments. In *Proc. 13th Intl. Pig Veterinary Society Congress*, 431. P. Poomvises and P. Ingkaninun, eds. Bangkok, Thailand: Chulalongkorn Faculty of Veterinary Science.

Corcuera, B. D., R. Hernandez-Gil, C. De Alba Romero, and S. Martin Rillo. 2002. Relationship of environment temperature and boar facilities with seminal quality. *Livestock Prod. Sci.* 74(1): 55-62.

Gates, R. S., and T. Banhazi. 2002. Applicable technologies for controlled environment systems (CES) in livestock production. In *Animal Production in Australia*, 486-489. D. K. Revell and D. Taplin, eds. Adelaide, South Australia: Australian Society of Animal Production.

Gates, R. S., J. L. Usry, J. A. Nienaber, L. W. Turner, and T. C. Bridges. 1991. An optimal misting method for cooling livestock housing. *Trans. ASAE* 34(5): 2199-2206.

Geers, R., B. Dellaert, V. Goedseels, A. Hoogerbrugge, E. Vranken, F. Maes, and D. Berckmans. 1989. An assessment of optimal air temperatures in pig houses by the quantification of behavioral and health-related problems. *Animal Prod.* 48: 571-578.

Jones, R., and C. J. Nicol. 1998. A note on the effect of control of the thermal environment on the well-being of growing pigs. *Applied Animal Behaviour Sci*. 60(1): 1-9.

Lopez, J., G. W. Jesse, B. A. Becker, and M. R. Ellersieck. 1991. Effects of temperature on the performance of finishing swine: Effect of a hot, diurnal temperature on average daily gain, feed intake, and feed efficiency. *J. Animal Sci.* 69(5): 1843-1849.

Lorschy, M. L., L. R. Giles, C. R. Smith, J. M. Gooden, and J. L. Black. 1993. Food intake, heat production, and milk yield of lactating sows exposed to high temperature. *Manipulating Pig Production* IV: 81. Attwood, Victoria, Australia: Australasian Pig Science Association

Madec, F., N. Bridoux, S. Bounaix, and A. Jestin. 1998. Measurement of digestive disorders in the piglet at weaning and related risk factors. *Preventive Vet. Med.* 35(1): 53-72.

Ouwerkerk, E. N. J., and S. Pedersen. 1994. Application of the carbon dioxide mass balance method to evaluate ventilation rates in livestock buildings. In *Proc. XII World Congress on Agricultural Engineering*, 516-529. Milano, Italy: CIGR.

Riskowski, G. L., and D. S. Bundy. 1990. Effect of air velocity and temperature on growth performance of weanling pigs. *Trans. ASAE* 33(5): 1669-1675.

SAS. 1989. *SAS/STAT User's Guide.* Version 6, 4th ed., vol. 2. Cary, N.C.: SAS Institute, Inc.

Seedorf, J., and J. Hartung, et al. 1998a. A survey of ventilation rates in livestock buildings in northern Europe. *J. Agric. Eng. Res.* 70(1): 39-47.

Seedorf, J., and J. Hartung, et al. 1998b. Temperature and moisture conditions in livestock buildings in northern Europe. *J. Agric. Eng. Res.* 70(1): 49-57.