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Publication date:
2018

Document version
Peer reviewed version

Citation for published version (APA):
Hansen, R. K., & Bjerg, B. S. (2018). *Natural ventilation's ability to prevent high indoor temperatures*. Paper presented at the XIX. World Congress of the International Commission of Agriculture and Biosystems Engineering (CIGR) , Antalya, Turkey.

Natural ventilation's ability to prevent high indoor temperatures

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Keywords: natural ventilation, finisher pigs, thermal comfort zone, exceeding ambient temperature

A desire to reduce energy consumption associated with mechanical ventilation in conventional pig housing has led to the development of a new hybrid ventilated building design, where large adjustable openings for natural ventilation are combined with a mechanical ventilation system for under floor removal and subsequent cleaning of a limited amount of air. To ensure competitive construction costs the building was designed with large building width (>50 m) which potentially is a challenge in relation to obtain sufficient ventilation in the entire animal occupied zone. Therefore, the aim of this study was to investigate to which extend it was possible to ensure satisfactory low ambient temperature for the animals in a wide hybrid ventilated building for finisher pigs when Danish summer conditions were considered.

Measurements were conducted in one 22 m long and 51 m wide section of the first hybrid ventilated building for finisher pigs, designed by the Danish company Agrifarm. Measured temperatures in six different pens were compared with outdoor temperature, room air temperature, and with estimated values for achievable pen temperatures by maximised utilization of the openings. The applied threshold for exceeding pen temperature was 24°C.

The data covered a warm summer period with small finisher pigs (336 hours), and a relative chilly summer period with large finisher pigs (850 hours). The average pen temperature was above 24°C in 60% of the time for the two periods together and for that percentage of time, the average pen temperature was 26.5°C and 26.7°C, which was 3.2°C and 5.4°C higher than the outdoor temperature for the two periods, respectively. In addition, there was a statistical significant difference of 2°C and 1.7°C between highest and lowest average measured pen temperature, for small and large pigs, respectively. The potential opening area for natural ventilation was fully utilised in 348 of the 535 hours where the average pen temperature was above 24°C. Calculated in relation to all 535 hours with pen temperature above 24°C the maximum achievable decrease was only 0.2°C.

In conclusion, the hybrid ventilated building was unable to keep the animals' ambient temperature down at a sufficient level for more than half the time, during summer, and full utilisation of the

natural ventilation had a negligible influence on reducing this temperature. To meet this challenge, it is suggested to investigate supplementary cooling methods.

Nomenclature

a	Opening area of section (m^2)
A	Area of the building's surface (m^2)
h	Height of window (m)
l	Length of window (m)
Max opening area	Maximum available opening area of building (m^2)
S	Specific heat of air ($Jm^{-3}°C^{-1}$)
T	Temperature (°C)
ΔT	Temperature difference between outdoor and indoor (°C)
U	Building's average U-value ($Wm^{-2}°C$)
v	Velocity in the openings (m/s)
Q	Ventilation airflow (m^3/s)
Φ_h	Heat supply from heaters (W)
Φ_s	Animals' sensible heat production (W)
θ	Angle of the maximum opening for a given window (°)

Subscripts

Modified	At maximised opening area (calculated)
Old	At actual opening area (measured)
Out	Outdoor
Pen	At pen level
Window	At given window

Introduction

Finisher pigs housed under undesirable high temperatures risk to develop heat stress. Heat stress is known for several negative physiological effects such as reduced growth, due to reduced feed intake and compromised gastrointestinal health (Ross *et al.* 2017). According to ASAE (1986), the highest feed efficiency for finisher pigs is found at ambient temperatures between 20 and 24°C. This complies with a comparison of published research results, showing the highest feed efficiency on average was found at an ambient temperature of 22.5°C (Hansen & Bjerg, unpublished). To consider uncertainties in the compared studies, the upper threshold temperature was set to 24°C in this work. Even in relative chilly summer periods, it can be challenging to keep the temperature below this threshold in the animal occupied zone. The ventilation system plays an essential role in cooling the pigs by fresh air supply. Most housing facilities for pigs in Denmark are equipped with a mechanical ventilation system for this purpose. This is energy consuming and is therefore associated with monetary costs (Andonov *et al.* 2003) and larger greenhouse gas emission. Natural ventilation is known to have considerable lower energy consumption than a mechanical system

(Bjerg *et al.* 2013; Chiumenti *et al.* 1989). Aiming an environment friendly livestock facility with low energy consumption, a new building concept recently arose in Denmark. This system has hybrid ventilation with partly natural ventilation and partly mechanical pit ventilation. The first of these finisher pig facilities was put into production in summer 2015 and consequently, the knowledge of its ability to keep the temperature within the pigs' thermal comfort zone, during summer, is scarce. The aim of this work is to investigate hybrid ventilation's ability to keep the temperature below the upper threshold temperature in the animal occupied zone, during summer.

Materials and methods

Facility and ventilation system

Measurements took place in a 22.40 m · 50.99 m sized section, consisting of two equally sized subsections with four rows of 10 pens each. All pens measured 5.20 m · 2.55 m with 1.60 m solid floor, 0.80 m drained floor (slatted floor with longer distance between the slots) and 2.70 m slatted floor and housed, in most cases, 17 pigs. The natural ventilation consisted of two openings above each other in the sidewall (h: 0.6m, l: 20.4m and h: 1.0m, l: 22.4m) one in the middle of the roof face (h:1.0m, l:22.4m) and one in ridge (h:1.0m, l:22.4m), on each side of the building. The upper sidewall, roof and ridge openings had a maximum opening angle of 90°, where the bottom sidewall opening was limited to 54°. Adjustment of the window openings was based on a room temperature set point of 19°C, but the opening area was corrected as the wind speed increased. With the applied correction, the maximum possible opening area for each of the building's openings appears from table 1, calculated based on Equation 1.

$$Max\ opening\ area_{window} = \sin(\theta) * h * l \qquad (1)$$

Table 1 Maximum opening area at different wind speeds

Wind speed, m/s	Bottom sidewall, m^2	Top sidewall, m^2	Roof, m^2	Ridge, m^2	Total, m^2
0	33.0	26.9	44.8	44.8	149.5
2	33.0	26.9	44.8	38.1	142.8
4	28.9	20.2	38.1	38.1	125.2
6	24.8	21.5	40.3	38.1	124.7
8	24.8	22.2	39.2	37.0	123.1
10	24.8	23.5	39.2	35.8	123.3
12	21.5	26.9	42.6	24.6	115.5
14	19.0	22.2	37.0	13.4	91.6
16	16.5	20.2	33.6	9.0	79.2
18	16.5	13.4	22.4	6.7	59.1
20	16.5	13.4	22.4	4.5	56.8

The mechanical pit ventilation worked at a constant effect of 14.1 m^3/hr/pig, which was automatically controlled based on data from integrated measurement wings.
In addition to the ventilation system, the building was equipped with high-pressure cooling sprinklers activated at outdoor temperatures above 23°C.

Data collection

The data collection was carried out in two periods to cover a situation with spring (mild weather) and large finisher pigs and a situation with summer (warmer weather) and small finisher pigs. Details of the data collection period are seen from table 2 and 3.

Table 2 Size and number of pigs in the two periods (Hansen 2016)

Pig size	Subsection	Period start	Period end	Weight start, kg	Weight end, kg	Number of pigs, start	Number of pigs, end
Large pigs	1A	04-05-2016	07-06-2016	84.9	118.8	665	661
Large pigs	1B	04-05-2016	07-06-2016	77.9	111.8	659	654
Small pigs	1A	11-07-2016	24-07-2016	40.3	73.6	679	677
Small pigs	1B	11-07-2016	24-07-2016	47.4	80.8	683	681

Table 3 Outdoor conditions during the two periods (Hansen 2016)

Period	Average outdoor temperature, °C	Minimum outdoor temperature, °C	Maximum outdoor temperature, °C	Average wind speed, m/s	Minimum wind speed, m/s	Maximum wind speed, m/s
Small pigs	20.21	11.48	31.38	1.82	<0.10	6.50
Large pigs	16.88	3.33	30.03	2.13	<0.10	9.47

Once every minute, VE10 temperature sensors (VengSystem A/S, Denmark) measured the pen temperature (height 0.7 m above floor) in pens located towards the middle in both subsection as number 2, 5 and 8 from the central aisle, and the value was logged. The room temperature was measured in the middle of each subsection (two sensors at each location), 1.5 m above floor (PT100 temperature sensors, Bitlink Interface Aps, Denmark). Information about wind speed, wind direction, outdoor temperature and rain was gathered by a weather station, placed on top of a neighbouring building. For detailed information about the building and management of the pigs, see Hansen (2016).

Data treatment

Aiming to investigate situations with too high pen temperatures, the applied dataset was restricted to hours with an average pen temperature above 24°C. SAS 9.4 and Microsoft Excel was used for data treatment. Data from the period with small and large finisher pigs, respectively, were treated individually.

First step was to identify hours with a potential for increased ventilation. This was done by restricting the dataset for hours where the opening area had been above 95 % of the possible. Next step was to identify the hours where the pen temperature could have been lowered to 24 °C or below by maximised opening area. A modified average pen temperature was then calculated, as the achievable pen temperature. The modified pen temperature, $T_{pen\ modified}$, was calculated both for a situation with limitation of the maximum opening area, due to increased wind speed (table 1), and a situation without these limitations, meaning that a maximum opening area of 149.5 m^2 could be reached independent of wind speed. Equation 2 was used for the calculation, under the assumption of Equation 3:

$$T_{pen\ modified} = T_{out} + \Delta T_{modified} \quad (2)$$

$$\Delta T_{modified} = \Delta T_{old} * \frac{1}{k} \quad (3)$$

The value of k depended on the expected primary driving force the natural ventilation. If the natural ventilation was wind driven, which was assumed at wind speeds above 1 m/s, k was calculated from Equation 4. This calculation assumed that the air exchange roughly could be assumed proportional to the buildings opening area.

$$k = \frac{Max.opening\ area}{Actual\ opening\ area} \quad (4)$$

The background for the assumption of proportionality was a rewrite of the building's heat balance, given by Equation 5.

$$\Phi_s + \Phi_h = Q * S * \Delta T_{old} + U * A * \Delta T_{old} \quad (5)$$

During summer, the only heat production in the building was the animals' sensible heat production, as heaters were turned off. Further, a large opening area was expected and the primary heat loss was expected through ventilation. In comparison, only a negligible amount of heat was lost as transmission heat loss and consequently this term was removed from the equation. The equation was then reduced to:

$$\Phi_s = Q * S * \Delta T_{old} \quad (6)$$

From Equation 6 it is seen that if the heat production was kept fixed and the air exchange would increase with a factor k then the temperature difference was reduced with a factor 1/k.

If the air exchange was driven by thermal buoyancy, which was expected at wind speeds below 1 m/s, then k was calculated from Equation 7.

$$k = \left(\frac{Max.opening\ area}{Actual\ opening\ area}\right)^{\frac{2}{3}} \quad (7)$$

Equation 7 is based on the assumption that the velocity in the openings, v, is proportional with the square root of ΔT_{old}, written in Equation 8.

$$v = k_1 * \sqrt{\Delta T_{old}} \qquad (8)$$

Where the assumptions that ΔT_{old} is inversely proportional with L (Equation 9) and that v is equal to L divided by the opening area, a (Equation 10), are inserted, resulting in Equation 11. k_1 and k_2 being constants.

$$\Delta T_{old} = k_2 * \frac{1}{L} \qquad (9)$$

$$v = \frac{L}{a} \qquad (10)$$

$$L = a^{\frac{2}{3}} * \left(k_1 * \sqrt{k_2}\right)^{\frac{2}{3}} \qquad (11)$$

Finally, boxplots were generated to compare room temperature with measured and modified pen temperatures. The boxplots showed the mean values, the 95 % confidence intervals, and the minimum and maximum values.

A CFD simulation of airflow in and around a corresponding pig section was used as aid to explain how the airflow could cause the observed temperature difference between pens. The conditions used for the simulation were that the wind direction was perpendicular to the building with a wind speed of 1 m/s. The opening areas in the used CFD model were a bit smaller than during the conducted measurement, and the design of the ridge openings were not completely comparable, whereas the remaining dimensions were. The CFD simulation was performed as describe in Bjerg *et al.* (2013), except that ventilations flaps were treated as interior and the outdoor temperature was set to 20 °C.

Results

In the period with small finishers, the average pen temperature exceeded 24°C in 125 out of 336 hours. In 15 out of the 125 hours with exceeding pen temperature, it would have been possible to increase the building's opening area. These observations had an average pen temperature of 26.8°C.

In the period with large finisher pigs, the average pen temperature exceeded 24°C in 410 out of 850 hours. In 172 of these hours, there was a potential to increase the opening area. The average pen temperature for the 172 hours was 26.6°C.

The CFD simulation result shown in figure 1 illustrates how the openings in the windward side of the building worked as inlets, and the openings in the leeward side of the ridge and the roof worked as outlets. Consequently, the lowest temperatures were found in the windward side, close to the central aisle. According to the simulation, only a few pens could provide a temperature below 24°C when the outdoor temperature was 20°C.

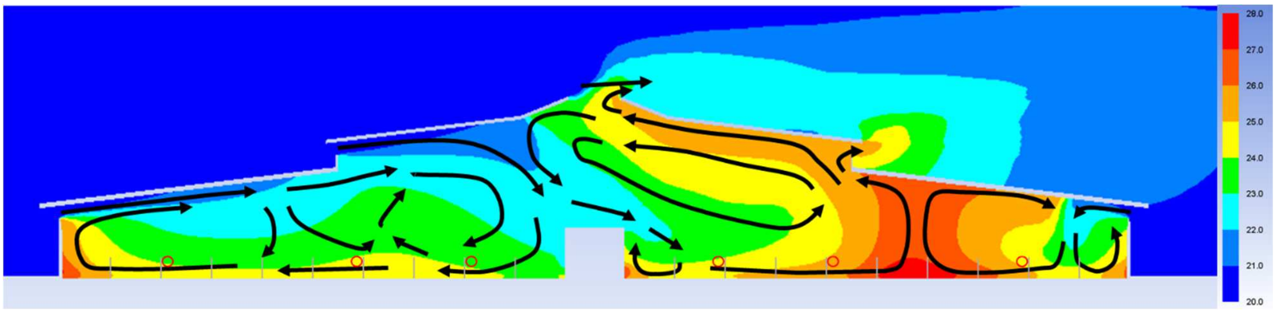

Figure 1 CFD simulation of airflow inside the building at 20 °C outdoor temperature and a wind speed of 1 m/s. The grey lines illustrates the pen partitions and the red circles the measurement points (pen 1-6 from windward side).

The temperature in pens across the unit was variating and for hours with an average pen temperature above 24°C, some pens provided an average temperature of approximately 25.5°C whereas other provided an average temperature of approximately 27.5°C, as illustrated in figure 2. Increasing the opening area to the maximum available, either with (w.l.) or without (wo.l.) limitations due to corresponding wind speed, did not affect the average pen temperature in the period with small finishers. With large finishers the average pen temperature showed a small, but significant reduction when the opening area was fully maximized without limitations to wind speed. With limitations, there was not seen a temperature reduction by increased opening area.

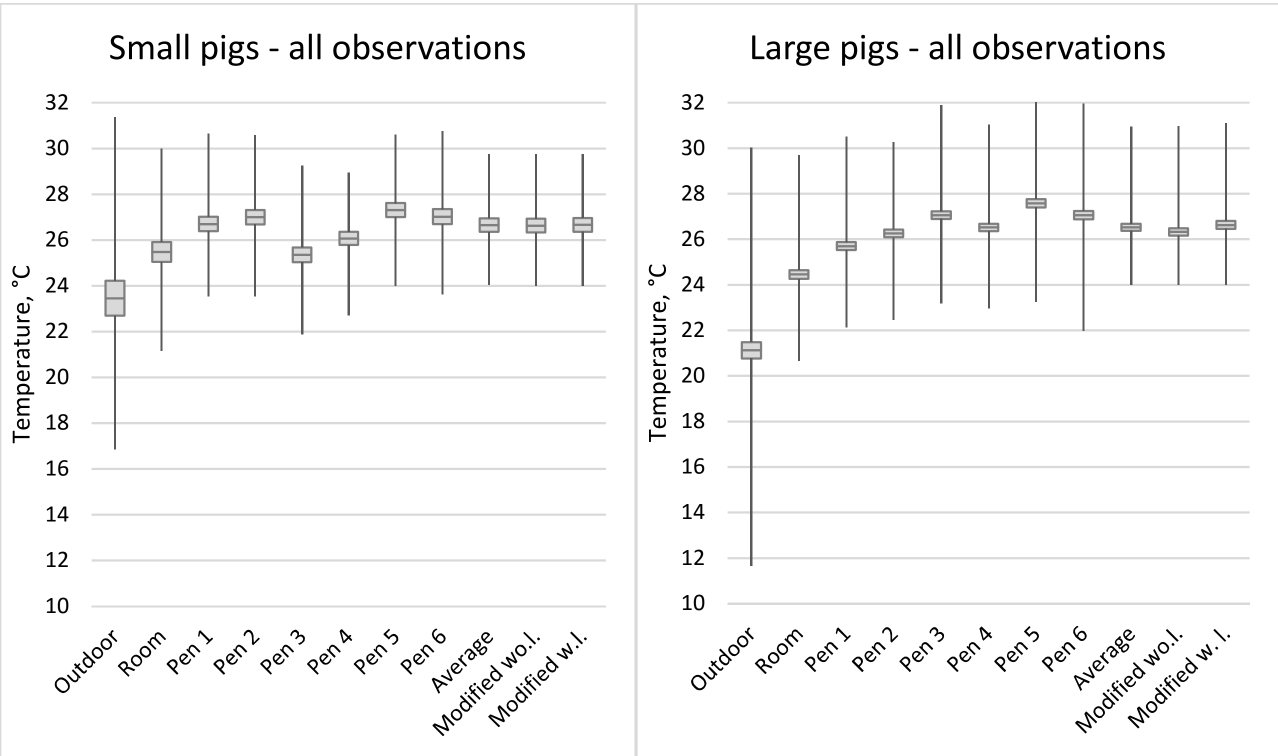

Figure 2 Boxplot showing mean value, 95% confidence intervals, and minimum and maximum values of measured outdoor, room and pen temperatures and modified pen temperature when small (left hand graph) and large (right hand graph) finisher pigs were housed

Discussion

The investigation of the hybrid ventilations ability to keep the temperature in the animal occupied zone below 24°C showed several hours with exceeding temperatures, in both periods. It was suggested that maximised utilisation of the openings of the natural ventilation system could prevent these exceeding temperatures to some degree. Calculation of the modified temperatures showed differently. When small pigs were housed under summer conditions, results showed no effect of increased opening area, in the hours where this would have been a possibility. This is explainable, as the opening area was already fully utilised in most hours with exceeding pen temperature (15 out of 125 hours). At the same time, the outdoor temperature was higher in this period, compared to the period with large finishers, which further reduces the ability to cool by ventilation with outdoor air. With large pigs, the opportunity to reduce the temperature by increased opening area was expected higher. This was because exceeding temperatures mainly originated from a larger heat production inside the unit, due to larger animals and lower outdoor temperatures. The expectation was supported by data showing a large number of hours with exceeding temperatures and a possibility to increase the opening area (172 out of 410 hours). Despite expectations, results showed no effect of increasing the opening area, when the maximum available area was limited to wind speed. Without these limitations, a small improvement in the pen temperature could be achieved, by increased natural ventilation. For the period with large finishers, the average pen temperature was 26.6°C for the hours with potential for increased opening and with a corresponding outdoor temperature of 21°C. The small influence of maximised opening area indicates that the total opening area was not big enough to provide sufficient air exchange in situations with large animals and moderate-warm weather. In investigated situations, results showed that the hybrid ventilation with a pit ventilation of 14.1 m^3/pig/hour and a natural ventilation system with 149.5 m^2 available opening area per section (1360 pen places) was not able to keep the temperature below 24°C for a considerable part of the time. However, this work only considered temperature. It is known that both humidity and velocity would affect the pigs' experience of the ambient temperature. Increasing velocity induces a chill effect and consequently, the experienced temperature will be lower than the measured (Bjerg *et al.* 2017). If the velocity induced by the natural ventilation had been included in the measurements, it would have been possible to give a more reliable picture of whether the temperatures above 24°C were critical for the pigs’ wellbeing.

Conclusion and perspectives

Results showed a considerable number of hours where pen temperatures exceeded the threshold of where the production performance was expected to begin deteriorate. This also applied for hours, where the ventilation openings were not fully utilised, which often occurred in the period when large finisher pigs were housed. However, subsequent calculations indicated a very limited potential to reduce pen temperatures in these periods by maximisation of existing openings. This potential was eliminated when considering the installed algorithmic for adjustment of the opening area in relation to wind speed.

Aiming to provide lower pen temperatures during summer, the next step would be to investigate supplementary cooling methods, for instance floor cooling in the existing floor heating pipes.

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