Computers and Electronics in Agriculture 149 (2018) 71–79

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Computational prediction of the effective temperature in the lying area of pig pens

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ARTICLE INFO

Article history:
Received 30 November 2016
Received in revised form 28 August 2017
Accepted 11 September 2017
Available online 27 September 2017

Keywords:
CFD
Effective temperature
Custom field functions
Thermal index
Pig
Ceiling jet inlet

ABSTRACT

Using solid floor instead of drained or slatted floor in the lying areas of pig pens has distinct advantages in relation to animal welfare, odour abatement and ammonia emission, energy consumption and reduced building costs. However, pig producers often opt out of providing a solid floor due to the risk of manure fouling in the lying area during warm periods, fouling that may increase work load, reduce animal welfare and degrade the indoor environment. The risk of fouling the lying area increases as indoor temperature increases, and it is therefore recommended that the indoor temperature should be maintained at around 13 °C during the last part of the growing period if diffuse air intake is used. Undesired higher indoor temperatures still occur during about 40% of the time each year, even in the relatively cold Danish climate (where outdoor temperatures average about 8 °C).

This study aims to investigate the potential benefits of using a hinged ceiling flap inlet to control the air velocity and experienced thermal environment for pigs in the lying area of finisher units. A new equation for the effective temperature (ET) has been developed and used to express how temperature, humidity and velocity, individually contribute to the combined effect of the thermal condition raising pigs are exposed to. Computational Fluid Dynamics (CFD) simulations were conducted to estimate the relevant parameters and, finally, the ET. Furthermore, the developed ET equation was implemented in the CFD model as a Custom Field Function to calculate the distribution of ET in the animal occupied zone. It was assumed that a traditional diffuse ceiling air inlet would deliver the required airflow rate as long as the outdoor temperature was below 10 °C. At higher outdoor temperature, a ceiling-jet inlet above each pen was opened gradually depending on the cooling requirements. When the inlet was only slightly open, it formed a wall jet attached to the ceiling. After reaching the end wall, the jet of air was deflected toward the lying area. When the jet inlet was more fully open, it sent the jet directly to the lying area.

Our investigations showed that the ceiling-jet inlet could be used to control air speed in the animal occupied zone and generate the same ET in the preferred lying area at a 9-degree higher outdoor temperature than if the same ventilation rate were delivered though the defuse ceiling only. This indicates that the periods of undesired high indoor temperature can be reduced from 40% to 5% of the time under Danish climate conditions. In addition, the results showed that the largest cooling effect was obtained when the ceiling-jet inlet was opened less than 30% due to the generation of the jet's being attached to the ceiling.

1. Introduction

To promote high performance and good animal welfare in intensive livestock production, it is essential to maintain a suitable thermal environment around the animals. The specific requirements depend on the design of the housing system. Using a solid floor as an alternative to a drained or slatted floor in the lying area of pig pens has distinct advantages in relation to (1) animal welfare (reduces e.g. adventitious bursitis (Mouttotou et al., 1998) and facilitates the used of straw), (2) low odour and ammonia emission (Pedersen and Jensen, 2010), (3) low energy consumption (due to reduced temperature requirement (Mount, 1975)), and (4) reduced building costs (savings in the cost of floor construction). Nevertheless, a solid floor is usually not selected by pig producers due to the risk of manure fouling in the lying area, which may increase the workload, imperil animal welfare and adversely affect the indoor air quality. In a controlled study that looked at growing-finishing

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https://doi.org/10.1016/j.compag.2017.09.016
0168-1699/

pigs kept in climate respiration chambers, Aarnink et al. (2006) demonstrated that fouling on a solid floor was at a constant low level as long the room temperature was maintained below a certain inflection temperature. They also found that fouling increases at room temperatures above this inflection temperature. In addition, the experiment showed that the inflection temperature was approximately 25 °C for pigs of 30 kg, and decreased to approximately 20 °C for pigs of 100 kg.

For commercial pig units with solid floors in the lying areas, Danish room temperature recommendations (Jensen and Rasmussen, 2011) are generally 5–7 °C lower than the inflection temperature found by Aarnink et al. (2006). This recommendation is based on practical experience showing that it is necessary to remain the temperature at such a low level to minimize fouling on the solid floor. The deviation in relation to the inflection temperature determined by Aarnink et al. (2006) may be due to differences between the conditions existing in the experimental study and those that are typical to Danish commercial pig farms, differences that include the following: (1) the number of pigs per pen was 5 in the experimental study but typically 15–20 in the commercial pig farms, (2) each pig was assigned a floor area of 1.0 m^2 in the experimental study whereas each pig is typically assigned around 0.7 m^2 in Danish commercial pig farms, (3) the pigs in the experimental study were exposed to a certain temperature for periods of one day only, whereas high temperature can occur over much longer periods at commercial pig farms, (4) the metal-slatted floor used in the experimental study might be less attractive as a lying area than the concrete-slatted floor used in Danish commercial pig farms, and therefore the pigs may be more reluctant to lie on the slatted floor, and (5) varying management practices may increase the fouling tendency in some commercial units or in some pens within a commercial unit.

The aforementioned Danish recommendation stipulates that for finishers the room temperature should be maintained at around 13 °C during the last part of the growing period if a diffuse-air inlet is used as the only inlet. As a consequence of this recommended low temperature, an undesirable high indoor temperature will occur about 40% of the time, even in the relatively cold Danish climate (an average outdoor temperature of around 8 °C).

Supplementary ceiling air-jet inlets can be an affordable option for increasing the air movement in the animal occupied zone during the warm periods. This measure will further cool the animals; however, the extent to which it can compensate for an undesirable high temperature is not clear.

An animal's perception of the thermal environment is affected by such physical parameters as air temperature, velocity, turbulence, humidity and the temperatures of surrounding surfaces. The integrated influences of these parameters are crucial when the animal experiences thermal stress or a change in behaviours. Over the last several decades, numerous indices or models have been suggested as ways to express the integrated effects of two or more of the above mentioned parameters. The Temperature Humidity Index (THI) is probably the most widely known of these indices and expresses the integrated influence of air temperature and humidity. Different constants of the THI equations were suggested for various categories of farm animal. For pigs, the constant can be found in investigations published by Ingram (1965) and Roller and Goldman (1969).

Bjerg et al. (2016) reviewed the publications relevant to thermal indices that include the integrated effect of at least temperature and air velocity. Seven indices were found to be related to cattle; two of these are specific to housed dairy cattle (Yamamoto et al., 1989; Baeta et al., 1987) and five to outdoor cattle (Gaughan et al., 2008; Eigenberg et al., 2005; Mader et al., 2006, 2010; Da Silva et al., 2015). In addition, Bjerg et al. (2016) found a single index concerning broilers (Tao and Xin, 2003) but none for pigs. Surprisingly, the review showed that none of the 8 published indices considered the physical heat transfer process stipulated that the expected chill effect caused by an increase in air velocity should be declined when the air temperature approaches the animal's body temperature. This serous limitation motivated us to develop a new index for estimating the extent to which an increased air velocity in the animal occupied zone can compensate for an undesired high temperature. We assessed the extent to which including supplementary ceiling air jet inlets would affect temperature, humidity, velocity and turbulence in the finishers' lying area and, consequently, we reviewed the literature searching for findings that could support the development of an index expressing the integrated effect of these four parameters. During the review, we realised that it was impossible to identify a suitable amount of data that would account for the effect of turbulence, and therefore we refrained from incorporating this effect in the model.

More than fifty years ago, Beckett (1965) suggested an effective temperature to express the combined influence that air temperature and air humidity may have on swine and determined the effective temperature to be equal to room temperature if the relative humidity were 50%. This approach inspired us to suggest that the integrated effect of the three parameters should be calculated as air temperature with separate terms for the effect of humidity and the effect of velocity, both expressed on a temperature scale. From Beckett (1965) we also adapted the name "Effective Temperature" (ET) and the value of 50% relative humidity as baseline for the effect of humidity.

Computational Fluid Dynamics (CFD) is an advanced and feasible tool for predicting the spatial distributions of the mentioned parameters in livestock rooms (Rojano et al., 2016; Rong et al., 2016). In addition, the Ansys Fluent (Ansys Inc.) software includes a component called Custom Field Functions (Ansys, 2013), which provides a user the possibility of predicting the spatial distribution of a customized parameter as a thermal index for integrating the effect of several parameters.

This study aims to investigate the potential of using a ceiling inlet to control the thermal environment, (including air speed), in the lying area of a pen for finishers. Our investigations sought to estimate the potential of a ceiling jet air inlet to reduce the number of hours of undesirable thermal conditions in the lying area.

2. Materials and methods

The first part of this section describes the development of the new ET index and the subsequent part focuses on development of a CFD model capable of predicting the spatial distribution of the developed index.

2.1. Development of an equation for ET that integrates influence of temperature, humidity and velocity

Effective Temperature (ET) is conceived by Beckett (1965) was used to evaluate the integrated effect that air temperature, humidity and velocity may have on animals. Available published data were used to develop an ET equation in which each physical property of air is considered independently, as shown in Eq. (1):

$$ET = T + E_{hum} + E_{vel} \tag{1}$$

where T is air temperature, E_{hum} and E_{vel} is the contribution of humidity and velocity to the ET, respectively, all expressed in °C. In this equation, the effect of humidity (E_{hum}) is assumed to be zero when the RH is 50%. Similarly, E_{vel} is set to be zero when the air speed is 0.2 m/s.

2.1.1. The effect of humidity

Beckett (1965) based the "Swine effective temperature" on a partitional heat loss diagram of a 67 kg growing pig and presented a graph to illustrate the combined influences of air temperature and humidity. We compared the values obtained from this graph (the nine combinations of three air temperature (29.4 °C, 32.2 °C and 35.0 °C) and three relative humidities (25%, 50% and 75%)) and found that the effect of humidity on ET can be calculated by Eq. (2):

$$E_{hum} = a(RH - 50)T \quad (R^2 = 0.99) \tag{2}$$

where RH is relative humidity, % and $a = 0.0007$.

Both Ingram (1965) and Roller and Goldman (1969) used the THI (Eq. (3)) to describe the relative influence of temperature and humidity.

$$THI = bT + (1 - b)T_{wb} \tag{3}$$

where T_{wb} is wet bulb temperature, °C and b is a constant that determines the relative influence of air temperature and the wet bulb temperature.

Ingram (1965) exposed four pigs aged 10–12 weeks to environments of six different combinations of dry and wet-bulb temperatures (T, °C/T_{wb}, °C: 32/22, 32/27, 36/23, 36/32, 40/26 and 40/36 respectively) and measured rectal temperature every 5 min for up to 70 min after the exposure began. The results were shown in a graph charting three levels of coefficient b (b = 0.15, 0.35 and 0.65), Eq. (3). It appeared that the correlation is closest where b = 0.65, but no correlation coefficients were mentioned.

Regarding b = 0.65, we analyzed the data to determine which value of the constant "a" resulted in the closest correlation between T + E_{hum} (Eq. (2)) and THI (Eq. (3)). The analysis was based on temperatures of between 10 and 40 °C and relative humidities of between 30 and 90%. The analysis showed that a = 0.0022 resulted in the closest linear correlation (R^2 = 0.999).

Roller and Goldman (1969) exposed 26 pigs weighing 76–119 kg to different heat exposures for 3 h. Two pigs were tested with respect to one of 13 combinations of temperature (34.4–42.8 °C) and dew point temperature (17.7–31.1 °C). Rectal temperature and ambient temperatures (dry-bulb and wet-bulb) were measured. The relative influence of wet-bulb temperature (namely the coefficient (1-b) in Eq. (3)) was examined in order to obtain the highest correlation coefficient of Eq. (3). According to a graph presented by the authors, the best correlation coefficient (r = 0.88) was found when the increase in rectal temperature after three hours' heat exposure was used as response variable, and this correlation coefficient was found to be b = 0.68. Based on the results related to all investigated response variables and an assumption that the response variable correlating best should count most, Roller and Goldman (1969) stated that using b = 0.75 in THI equation would be the most precise for a single indicator of thermal environment imposed.

Using the same procedure as mentioned above, it was estimated that b = 0.75 was equivalent to a = 0.0015 (R^2 = 0.999). This value was similar to the mean of the values derived from each of the three investigations (Beckett, 1965; Ingram, 1965; Roller and Goldman, 1969), and in this study was used in Eq. (2) to calculate the effect of humidity on ET.

2.1.2. The effect of velocity

The effect of velocity on ET expressed by Eq. (4) assumes that the chill effect of increased air velocity declines when the air temperature approaches the animal body temperature. It also assumes that the chill effect is proportional to a power function of air velocity and that the chill effect should be zero at a velocity of 0.2 m/s.

$$E_{vel} = c(d - T)(v^e - 0.2^e) \tag{4}$$

where v is the velocity magnitude (m/s), c is a constant, d is the temperature where increased air velocity no longer provides any chill effect (°C), and e is a constant that represents the power of velocity.

The only data we found concerning live pigs and that could be suitable for determining the three constants in Eq. (4) was obtained by Mount and Ingram (1965). The authors measured the effect of ambient temperature and air velocity on sensible heat lost from two pigs in each of three different weight ranges (3.4–5.8, 20–25 and 60–70 kg). The experiments were conducted with a heat flux sensor (Hatfield, 1950) strapped to the dorsal thorax of the pigs while they were being kept individually in a cage with closed sides. Above the cage, a variable speed fan directed airflow vertically into the cage, and the air speed was measured 5–10 cm above the heat flow disc. Body temperatures, environmental temperatures and heat loss were measured every 5 min until four readings had indicated that a steady state had been reached. The measurements were conducted at air speeds of 0.08, 0.35, 0.60 and 1.00 m/s for each of five ambient temperatures (35, 30, 25, 20 and 15 °C). We investigated to find which power of velocity (e) produced the best agreement between $T + E_{vel}$ and the sensible heat loss determined by Mount and Ingram (1965). For all three weight ranges, the best agreements (R^2 = 0.96, 0.98 and 0.92) were found when the power of velocity was around 0.5; however, agreement was scarcely affected when the power of velocity (e) was changed within a range of between 0.4 and 0.8.

Li et al. (2016) used CFD to study the convective heat transfer occurring in pig models inside a virtual wind tunnel and found that the convective heat transfer coefficient for a geometrical model of a standing pig was proportional to the 0.66 power of the air velocity. Therefore, we decided to use this value for the constant e in Eq. (4). At that value, the best correlation between $T + E_{vel}$ and the results presented by Mount and Ingram (1965) was found at c = −1.0 and d = 42. And at these values, the coefficient of determination was 0.96, 0.97 and 0.91, respectively, for each of the three levels of body weight, see Fig. 1.

In the absence of additional available data on pigs, we investigated how well the ET agrees with measurements conducted by Tao and Xin (2003) and used in their development of the Temperature-Humidity-Velocity Index (THVI) for hens. Their study used market-size broilers and collected experimental data pertaining to body-temperature as it increased over a 90-min period after the hens were exposed to 18 different heat stress conditions, i.e., three levels of air temperature (35 °C, 38 °C and 41 °C), two levels of dew point temperature (19.4 °C and 26.1 °C) and three levels of air velocity (0.2, 0.7 and 1.2 m/s). By using these experimental data, Tao and Xin (2003) were able to develop a temperature-humidity-velocity index, as described in Eq. (5):

$$THVI = (0.85T + 0.15T_{wb})v^{-0.058} \quad (0.2 \leqslant v \geqslant 1.2) \tag{5}$$

We investigated how well the same data were reflected when using Eq. (6) to calculate ET and considering the effects of humidity and velocity (insertion of Eqs. (2) and (4) in Eq (1)):

$$ET = T + 0.0015(rh - 50)T + \left(-1.0(42 - T)(v^{0.66} - 0.2^{0.66})\right) \tag{6}$$

This resulted in a coefficient of determination of 0.97 for the correlation between ET and the data presented by Tao and Xin (2003). The broiler body temperatures are plotted versus THVI and ET, and as Fig. 2 shows, the ET equation correlates considerably better with the used data than with that calculated using the THVI equation.

Based on the above analysis, we used the values of c = −1.0, d = 42 and e = 0.66 to calculate the effect of velocity on ET.

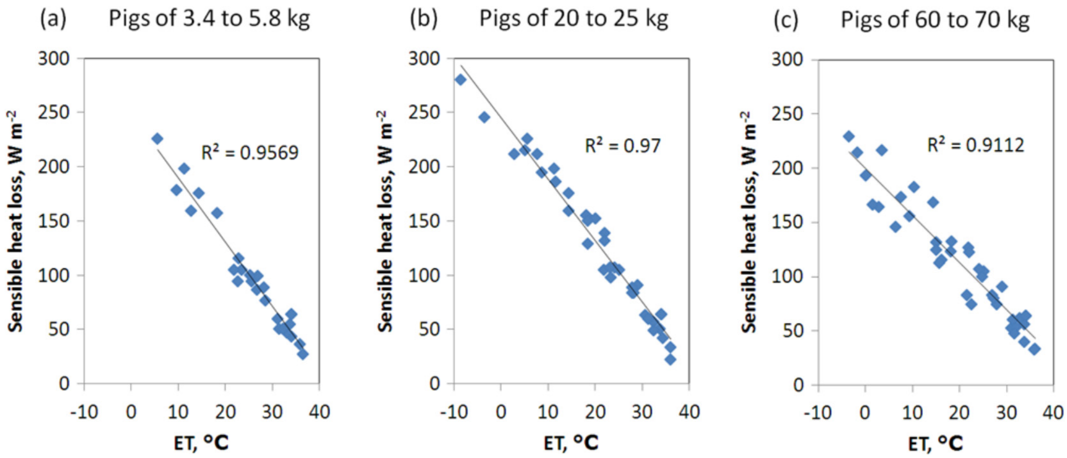

Fig. 1. Sensible heat loss for pigs at different ETs calculated as $T + E_{vel}$ assuming c = −1.0, d = 42 °C and e = 0.66. Data originates from Mount and Ingram (1965) and includes exposure to different ambient temperatures (15, 20, 25, 30 and 35 °C) at different air speeds (close to 0.08, 0.35, 0.60 and 1.00 m/s). The three graphs represent different weight ranges.

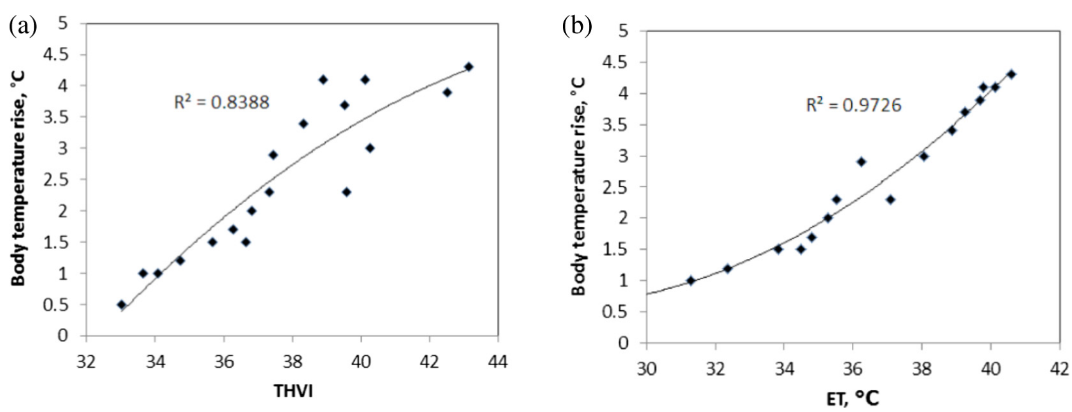

Fig. 2. Comparison of measured and predicted body temperature rise for broilers exposed to 18 different combinations of dry-bulb temperature, dew point temperature and air velocity as function of (a) THVI (Eq. (5)) and (b) ET (Eq. (6)).

2.2. CFD modelling

CFD modelling was applied to predict the parameters required to estimate the ET (Eq. (6)) in the lying area on the solid floor of a pen for growing pigs. We assumed a diffuse ceiling air inlet supplied the required airflow rate whenever the outdoor temperature was below 10 °C. At higher outdoor temperatures, a ceiling jet inlet above each pen was regulated gradually to create an attached wall jet that passed along the ceiling and then down into lying area near the end wall of the pen.

The study involved a finisher unit with one row of pens on both sides of a 1.0 m wide longitudinal aisle, where each pen was 5.2 m long and 2 m wide, see Fig. 3.

The ceiling height was 2.6 m, and the thermal insulation of building corresponded to normal Danish practices. The building was equipped with an air intake that brought in air through the attic and a porous ceiling that allowed diffused air into the animal room. In addition, an air jet inlet was centred in the ceiling above each pen. The ceiling inlet was modelled as a DA 1800 Ceiling Inlet from Skov (SKOV A/S, Denmark, www.skov.com), and if the flap were directed downward the free opening was 0.15 m^2. At small openings, the flap directed the jet against the wall, where it was deflected and continued down along the wall to reach the animal occupied zone. At larger openings, the flap directed the jet directly into the animal occupied zone.

Each pen accommodated 15 pigs, each weighing about 90 kg to represent the last part of growth period where the recommended temperature should be the lowest. Equations from CIGR (2002) were used to estimate the heat production value for pigs kept at 19 °C, and the values were 140 W of sensible heat and 0.16 kg of water evaporation pig^{-1} h^{-1}.

The standard k-ε turbulence model (Launder and Spalding, 1974) were used to calculate the velocity, temperature and humidity distribution in one half pen section of the room, including the attic above. The CFD solution method included the SIMPLE scheme for the pressure velocity coupling and the Second Order Upwind scheme for discretization of the governing equation. Enhanced wall treatment was applied, and Y^+values were less than 300. A converged solution was assumed to be reached when the scaled residuals for all solved equations were $<10^{-5}$, and the average values of velocity, temperature and the mass fraction of H_20 in the preferred lying area (see Fig. 3) were stable. The latter was defined as a relative difference of less than 0.01% over 100 iterations.

The volume included in the simulation was divided into 257,565 hexahedral cells, and the grid on surfaces and the used boundary conditions (BC) are shown in Figs. 4 and 5.

The geometrical model was prepared in such a way that the inlet bringing air from the attic to the room below could do so either exclusively through the porous layer in the ceiling or through the porous layer and in combination with the ceiling jet

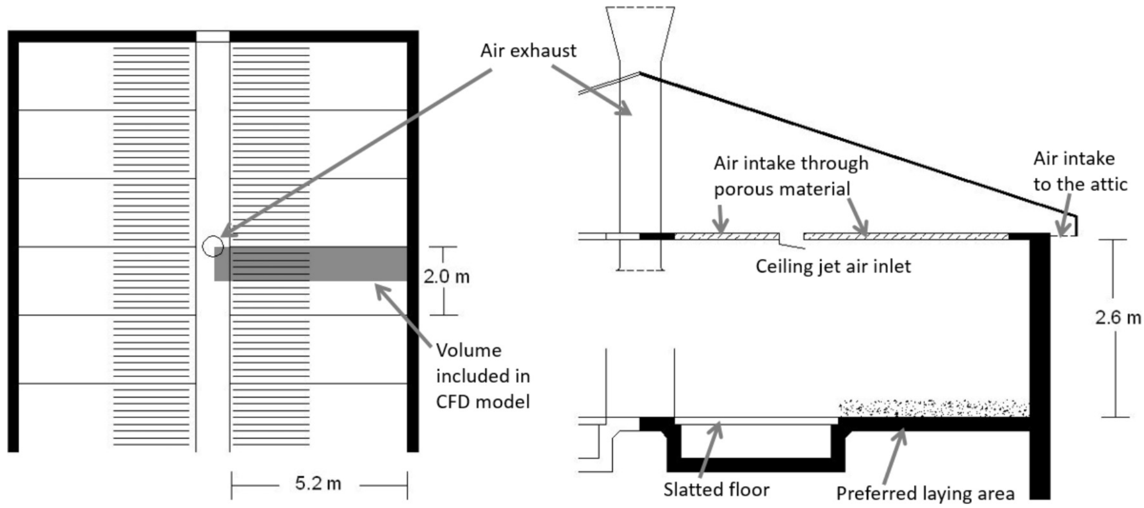

Fig. 3. Plan and cross section of the studied finisher unit.

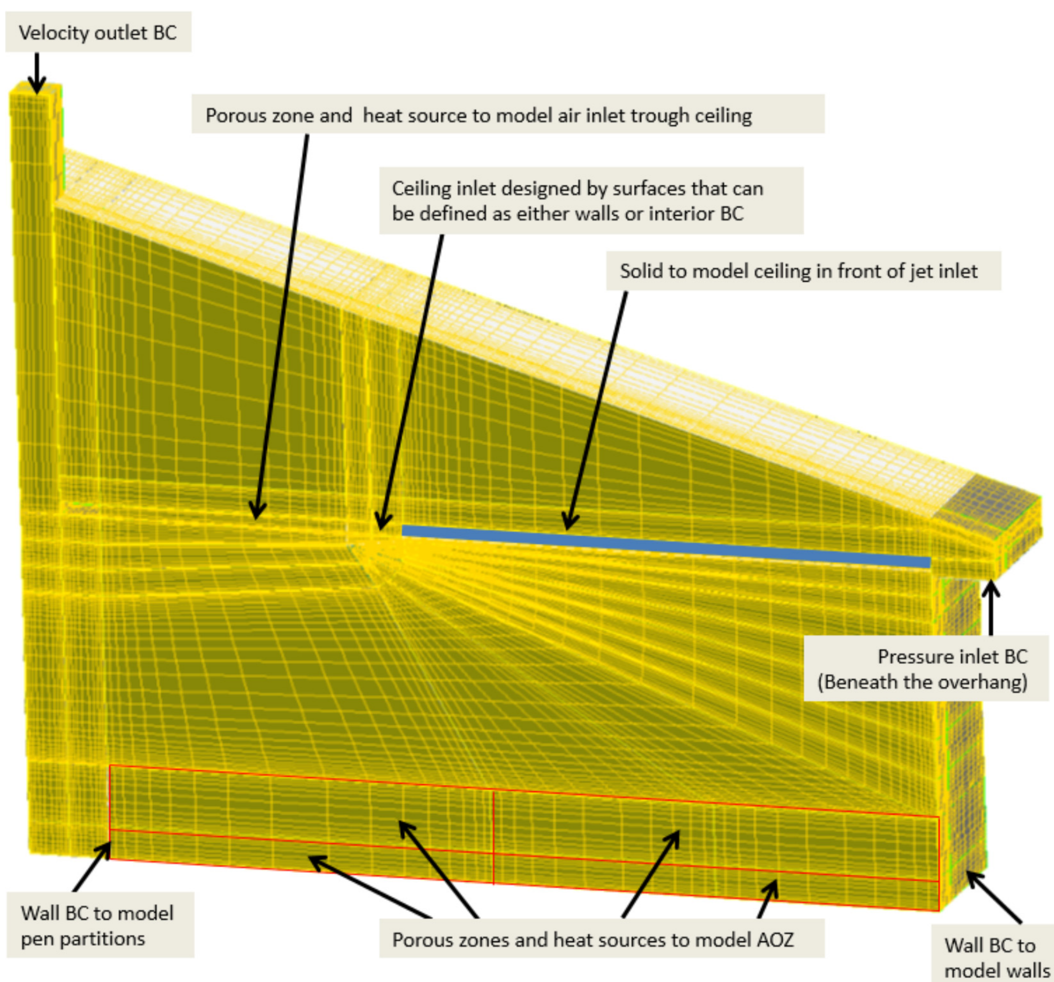

Fig. 4. Grid on surfaces and boundary conditions (BC) for the used geometrical model.

inlet. The latter could be adjusted to different opening angles (thus, the opening areas) by assuming that different predefined surfaces were set to be either wall BC or interior (see Fig. 5 and Table 1).

The porous layer in the ceiling and in the animal occupied zone was modelled as porous media cell zones, as suggested by Bjerg et al. (2011). Prior simulations had shown that the assumption of a porous media cell zone, to an unrealistically large extent, restricts the airflow along the porous zones and, therefore, we modelled the ceiling in front of the jet inlet as a solid wall (see Fig. 5). The air flow through the remaining part of the porous material in the ceil-

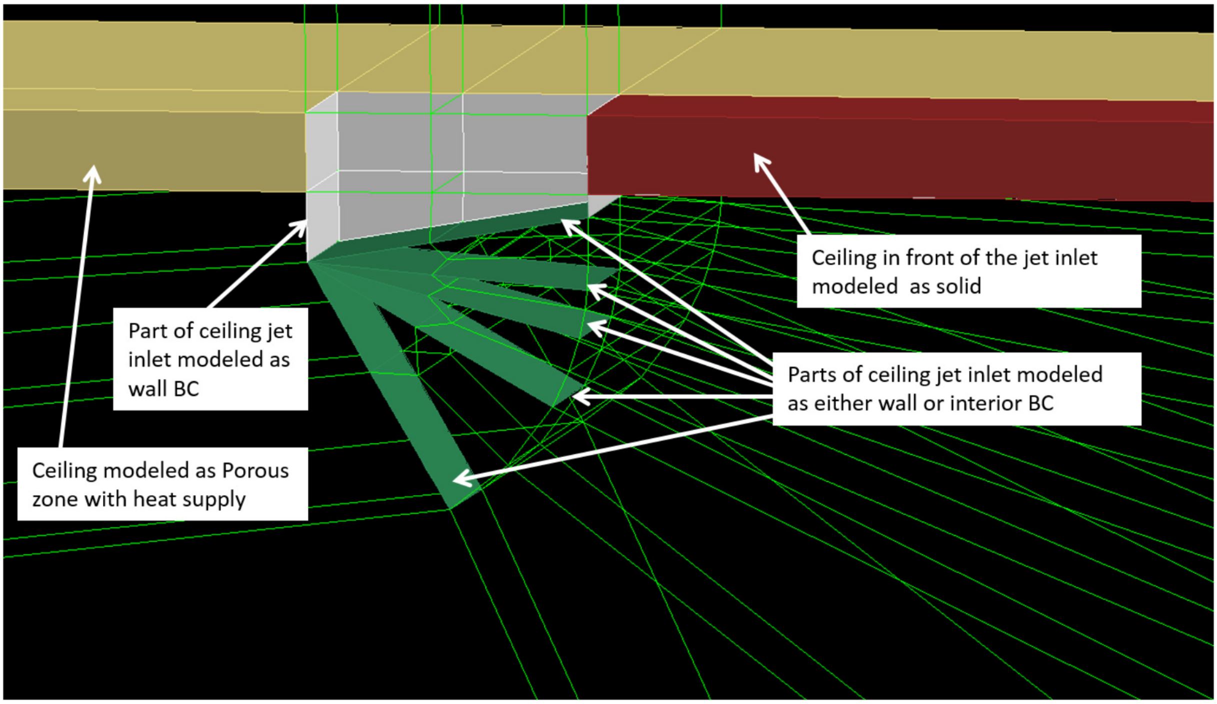

Fig. 5. Boundary conditions (BC) around the assumed ceiling jet inlet. Green lines indicate the block structure of the used hexahedral grid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Assumptions used and results of simulation 1a–5b. Simulations to which was added an 'a' ignore any presence of pigs (which would restrict the airflow in AOZ), and simulations to which were added a 'b', include the porous media assumption required to model how the animals restrict the air movement.

Simulation #	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b
Assumptions										
Outdoor air temperature, °C	10.0		17.0	17.6	19.2	19.0	16.5	14.6	18.8	17.8
Relative humidity in outdoor air, %	82		73	72	66	67	74	79	67	71
Ceiling inlet flap direction	Closed		−5 degree		−15 degree		−30 degree		−60 degree	
Results										
Pressure drop over the ceiling, Pa	30		14		10		8		6	
Airflow of the ceiling jet, $m^3\ h^{-1}\ pig^{-1}$	0		54		67		73		80	
Average ET in the PLA, °C	14.7	19.0	14.7	19.0	14.7	19.0	14.7	19.0	14.7	19.0
Minimum ET in the PLA, °C	11.2	14.6	11.5	15.6	11.7	15.0	6.8	11.9	5.5	8.8
Average temperature in the PLA, °C	17.0	17.6	20.7	21.3	22.7	22.4	20.5	19.0	22.7	21.7
Average effect of humidity in the PLA, °C	0.7	0.7	0.5	0.4	0.3	0.4	0.6	0.7	0.4	0.5
Average effect of velocity in the PLA, °C	−2.9	0.7	−6.5	−2.7	−8.3	−3.8	−6.2	−0.6	−8.4	−3.3

ing was assumed to be proportional to the pressure drop over the ceiling, and it was modelled so that an airflow of 100 $m^3\ h^{-1}\ pig^{-1}$ caused a pressure drop of 30 Pa when only the diffuse inlet was used. Laminar flow conditions were assumed in the porous cell zone in the ceiling so that there would be no over estimation of the heat and moisture diffusion occurring through the ceiling. Simulations marked with an 'a' in Table 1 ignore the fact that the animal restricts the flow, and the simulations marked with a 'b' use the porous media assumption to model how much the animal restricts the air movement, as suggested by Bjerg et al. (2011).

Half of the sensible heat released from the animals was assumed to be transferred to the air in the animal occupied zone, and the larger part (70%) of it was distributed in what we defined as the preferred lying area (PLA), which encompassed a zone extending from 0 to 2.8 m from the end wall of the pen to up to 0.25 m above the floor (see Figs. 3 and 4). The other half of the sensible heat released was assumed to be transmitted out of animal occupied zone as radiation. A minor part (3%) of this share was assumed to equalize the transmission heat from the building and was consequently excluded from the calculation. The remaining part of the radiation was distributed in the cell zone used to model the porous material in the ceiling, and it returned to the room via the airflow passing through the porous ceiling.

Seventy percent of animal moisture production was assumed to be released in the PLA and 30% in the remaining part of the animal occupied zone.

The assumed relative humidity of the outdoor air was calculated by classifying the hourly values of relative humidity in Danish climate data reported by Møller and Lund (1995) into one-degree temperature intervals. The average relative humidity in each interval between 10 and 25 °C was subsequently related to the temperature which resulted in the polynomial relationship mentioned in Eq. (7) ($r^2 = 0.99$):

$$RH = 0.0183T^3 - 1.0466T^2 + 16.754T + 0.7499 \tag{7}$$

Eq. (6) and the separate effects of humidity and of velocity included in Eq. (6) were implemented in ANSYS Fluent as Custom Field Functions.

Simulation 1a and 1b assumed a closed jet inlet, outdoor temperature of 10 °C and an air change of 100 $m^3\ h^{-1}\ pig^{-1}$. The estimated average ET in the PLA was 14.7 and 19.0 °C, respectively, without and with the porous media assumption applied to the animal occupied zone. These values were used as upper threshold for well-functioning pens with solid floors in the lying area. In the subsequent simulations, it was investigated to which extent the use of the ceiling jet inlet could create a similar ET in the PLA at higher outdoor temperatures. The method for adjusting the outdoor temperature to obtain the same ET in the PLA was chosen because it facilitated (1) use of the same assumptions for animal heat release in all simulation, (2) comparison of parameters (as the effect of velocity) at the same ET, and (3) reduction of the number of simulations required to fulfil the aims of the study.

3. Results and discussion

Based on the results of simulation 1, the assumed upper threshold for the thermal conditions in PLA was an ET of 14.7 or 19.0 °C depending on whether the porous media assumption was applied to the AOZ. In simulation 2, the ceiling inlet flap were assumed to point five degrees downward, and the outdoor temperature was increased to a degree at which the ET reached the same levels as in simulation 1a and 1b, respectively. The result was that the same ET could be retained at an approximately 7-degree higher outdoor temperature, nearly regardless of whether or not the porous media assumption was applied to the AOZ. As shown in Table 1, opening of ceiling jet inlet to the 5-degree downward position reduced the pressure drop over the ceiling from 30 to 14 Pa, and the air passing through the jet inlet amounted to 54 of the total 100 $m^3\,h^{-1}\,pig^{-1}$.

In simulation 3, the ceiling inlet flap pointed 15 degrees downward, and the same ET could be retained at a 9-degree higher outdoor temperature compared to when the diffusion inlet only was used. Fig. 6 shows the distribution of temperature, relative humidity and velocity in the symmetry plan obtained from simulations 1a, 3a and 5a, and it shows that the jet attached to the ceiling and to the end wall when the ceiling inlet was pointed 15 degrees downward.

In simulation 4 the inlet flap pointed 30 degrees downward, and the jet was no longer attached to the ceiling; however, the free jet pointed toward the lower part of the end wall. This position was less effective at chilling the animals in the PLA than when the flap was pointed 5 or 15 degrees downward. This result is most likely caused by the lower initial velocity and faster decay of the velocity of the free jet compared to that of the attached jet.

The inlet flap pointed 60 degrees downward in Simulation 5, and the jet blew toward the front of the PLA. The outdoor temperature was increased to either 18.8 or 17.9 °C depending on whether or not the porous media were used to restrict the airflow in the AOZ to maintain the same ET level at the PLA.

The relative humidity in the PLA was in all cases above 50%, and, therefore, it contributed positively to the ET. However, as shown in Table 1, the effect of the humidity in all cases was between 0.2 and 0.7 °C, which is a relatively small effect.

As shown in Table 1, the estimated effect of velocity varies from -8.4 to 0.7 °C. As expected, the highest values were found in the case that did not include the ceiling jet inlet and used a porous media modelled at the AOZ to restrict the airflow. The flow restriction that occurred porous media was assumed in the AOZ decreased the chill effect that velocity had on ET in the PLA by

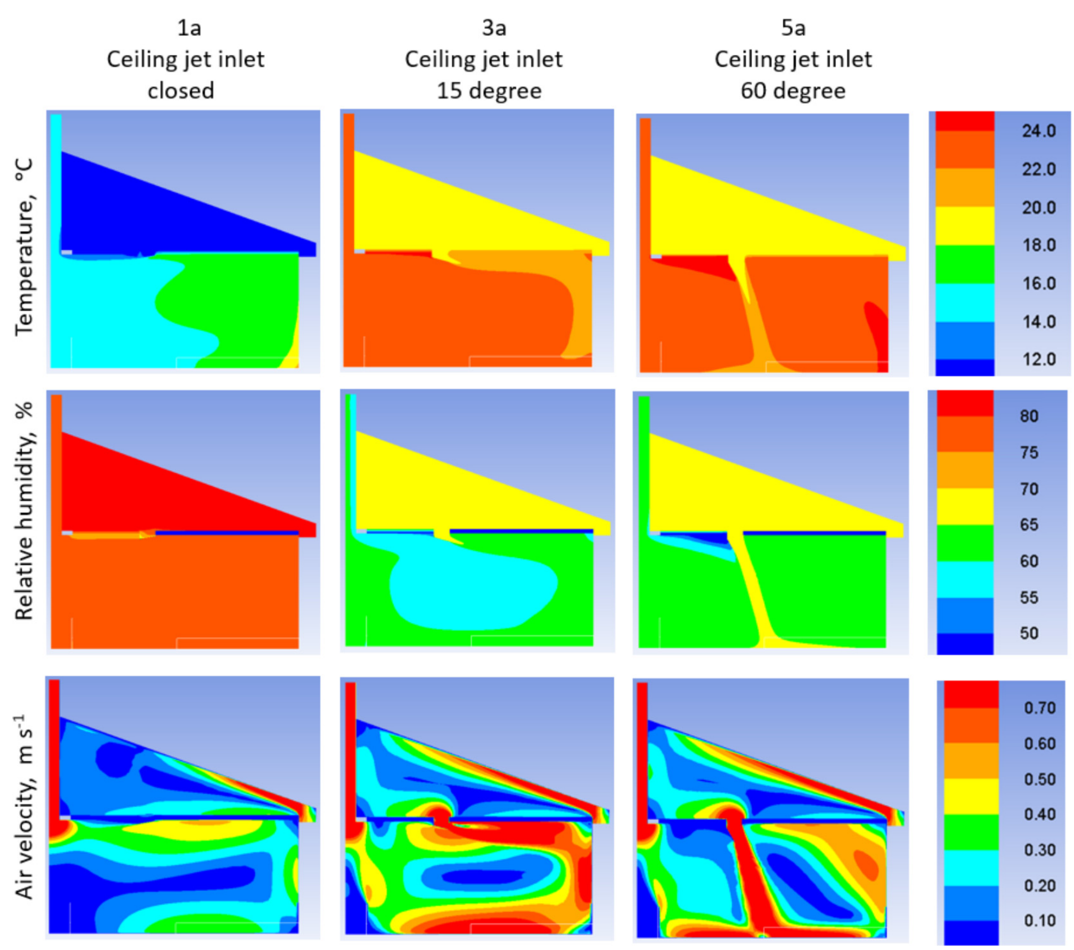

Fig. 6. Simulated distribution of air temperature, relative humidity and velocity and in the symmetry plane of the pen in simulation 1a, 3a and 5a.

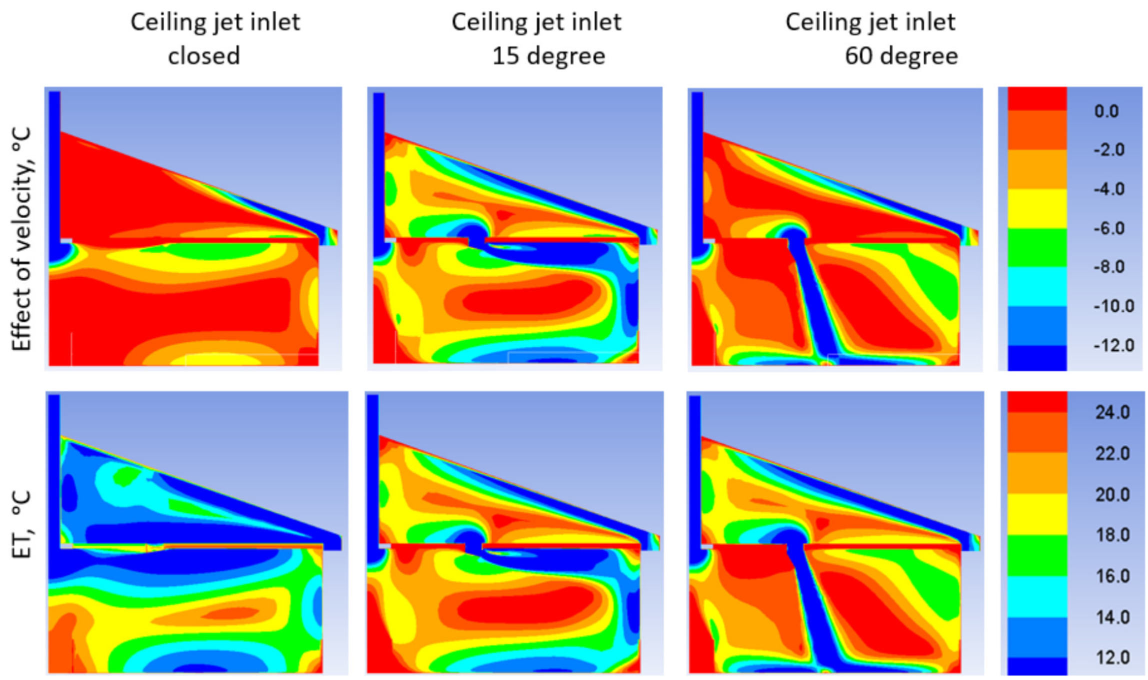

Fig. 7. Simulated distribution of the effect of velocity and ET in the symmetry plane of the pen in simulation 1a, 3a and 5a.

3.6 to 5.6 °C. Thus, a difference of up to 2 °C between the different ventilation configurations occurred when the porous media assumption, was included; however, a comparison of the outdoor temperatures mentioned in Table 1 showed that the order of the five ventilation configurations regarding their ability to chill the animals was the same with or without the porous media assumption included.

Given the presented results, it seems clear that the amounts of humidity contributed to the ET in the PLA were small in this study, whereas the main contributions came from temperature and velocity. Fig. 7 shows the distribution of the estimated effect of velocity alone and of ET in the cases of 1a, 3a and 5a. In addition to a suitable average ET in the PLA it may be important to avoid that the temperature in some parts of the PLA is significantly lower or higher than average, which may cause the animals to avoid parts of the PLA. As shown in Table 1, the minimum ET in the PLA was apparently lowest in simulation 5, which included a free jet, and highest in simulation 2 and 3, both of which included an attached jet. This indicates that the jet attached to the ceiling produces a more uniform ET in the PLA compared to the case involving a free jet or when the air is supplied through the diffusion ceiling only.

Our results show that the ET in the PLA can be maintained at the same level by regulating the opening of the ceiling jet inlet even when the outdoor temperature rises from 10 to 19 °C. This also indicates the possibility of using a solid floor as an alternative to a drained and slatted floor with a well-controlled thermal environment in the lying area. Using a combination of diffusion ceiling inlet and a ceiling jet inlet control can reduce the periods of undesired high indoor temperatures, expressed in hours yearly, from 40% to 5%.

The attached jets produce a greater and more uniform chilling effect than do free jets. This could inspire future investigations of ways to improve the setup. Such improvements might include moving the inlet closer to the wall (and thereby reducing distance the jet of air must travel to reach the animals), adding a rounded transition between the ceiling and wall, or changing of the geometry of the ceiling inlet so that the attached jet could be retained at a more widely opened inlet position.

The geometrical model used in the CFD simulation had an advantage in that it solved the question of whether to divide the flow between the porous ceiling and the ceiling jet inlet. However, it did not fully solve the challenge that is relevant to the porous zone modelling. In ANSYS Fluent, the velocity gradient is handled differently between the surface of a porous zone and a wall surface, regardless the resistance parameters are set so high that the porous cell zone should react as a solid (Virding, 2015). The problem is that the software do not support the use of wall functions at porous media cell zones, and the practical implication is that air velocity along the porous media cell zone becomes unrealistically low. To some extent, this study accounted for the limitation by assuming that the ceiling in front was a solid, see Fig. 5. However, the jet also expanded in width, and consequently a part of jet continued to flow along the porous media; this might have contributed to the jet's decreased momentum. Therefore, using CFD methods in the future to optimize the chilling effect of ceiling inlets, including a wall BC (or solid) at the entire ceiling in front of the inlet should be considered because this naturally required an alternative method to handle the influence of the air intake through the porous material in the ceiling.

4. Conclusions

Reported studies on pigs' response to warm conditions and on CFD methods to determine the convective heat removal from pig models were utilized to develop a new model for effective temperature (ET) that express how temperature, humidity and velocity, individually contributes to the united effect of the thermal condition that growing pigs are exposed to. The ET model was implemented into ANSYS Fluent as Custom Field Functions and used to calculate the thermal condition in the PLA of pen for growing pigs.

The study investigates the effect of supplementing ceiling jet inlets to a diffusive air inlet (porous material) on thermal environment at of the PLA. The air stream created by the ceiling-jet inlets decreases the periods during which the thermal conditions contribute to the risk of fouling in the lying area. The ET in the PLA with an outdoor temperature of 10 °C and maximum ventilations (100 $m^3 h^{-1} pig^{-1}$) without the ceiling-jet inlet were used as a threshold to mark when fouling could increase. The results showed that the ceiling-jet inlet made it possible to maintain the same ET in the PLA even when the outdoor temperature increased to 19 °C. As a result of this increased efficiency, the time during which pens should function well would increase significantly—from 60 to 95 percent of the yearly hours of use (under Danish climate conditions).

The opening size of the used ceiling-jet inlet was crucial for the chilling effect in the PLA, and the most effective and uniform chilling occurred when the opening size was sufficiently small to maintain a jet attached to the ceiling. Applying the porous media assumption to the AOZ of the model decreased the chilling effect that velocity had on the ET in the PLA by 3.6–5.6 °C. The difference in the effect produced when a porous media was assumed was so small regardless of ventilation configuration (up to 2 °C) that it did not matter whether or not the qualitative comparison of the different configurations was based on the simulations that included the porous media assumption in the AOZ.

Funding

This work was supported by Innovation Fund Denmark.

References

Aarnink, A.J.A., Schrama, J.W., Heetkamp, M.J.W., Stefanowska, J., Huynh, T.T.T., 2006. Temperature and body weight affect fouling of pig pens. J. Anim. Sci. 84, 2224–2231.
ANSYS, 2013. ANSYS Fluent Users Guide, Release 15. ANSYS Inc.
Baeta, F.C., Meador, N.F., Shanklin, M.D., 1987. Equivalent temperature index at temperatures above the thermoneutral for lactating cows. ASAE meeting paper.
Beckett, F.E., 1965. Effective temperature for evaluating or designing hog environments. Trans. ASABE 8 (2), 0163–0166.
Bjerg, B., Wang, X., Zhang, G., 2016. The effect of air velocity on heat stress at increased air temperature. In: CIGR-AgEng Conference, June 26–29, 2016 Aarhus, Denmark.
Bjerg, B., Zhang, G., Kai, P., 2011. CFD analyses of methods to improve air quality and efficiency of air cleaning in pig production. In: Mazzeo, N. (Ed.), Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality. InTech. Chapter 24; ISBN 978-953-307-316-3.
CIGR, 2002. Forth Report of Working Group on Climatization of Animal Houses. CIGR. Research Centre Bygholm, Horsens, Denmark. ISBN 87-88976-60-2.
Da Silva, R.G., Maia, A.S., de Macedo Costa, L.L., 2015. Index of thermal stress for cows (ITSC) under high solar radiation in tropical environments. Int. J. Biometeorol. 59, 551–559.
Eigenberg, R.A., Brown-Brandl, T.M., Nienaber, J.A., Hahn, G.L., 2005. Dynamic response indicators of heat stress in shaded and non-shaded feedlot cattle, part 2: predictive relationships. Biosys. Eng. 91 (1), 111–118.
Gaughan, J.B., Mader, T.L., Holt, S.M., Lisle, A., 2008. A new heat load index for feedlot cattle. J. Anim. Sci. 86 (1), 226–234.
Hatfield, H.S., 1950. A heat-flow meter. J. Physiol. 111. Proceedings of the Physiological Society 16–17 December 1949.
Ingram, D.L., 1965. The effect of humidity on temperature regulation and cutaneous water loss in the young pig. Res. Vet. Sci. 6, 9–17.
Jensen, T., Rasmussen, H.M., 2011. Delvis Spaltegulv (in Danish). Danish Pig Research Centre Homepage <http://vsp.lf.dk/Viden/Stalde/Staldindretning/Slagtesvinestald/Delvist%20spaltegulv.aspx?full=1>. accessed November 29 2016.
Launder, B.E., Spalding, D.B., 1974. The numerical computation of turbulent flows. Comput. Methods Appl. Mech. Eng. 3, 269–289.
Li, H., Rong, L., Zhang, G., 2016. Study on convective heat transfer from pig models by CFD in a virtual wind tunnel. Comput. Electr. Agric. 123, 203–210.
Mader, T.L., Davis, M.S., Brown-Brandl, T., 2006. Environmental factors influencing heat stress in feedlot cattle. J. Anim. Sci. 84 (3), 712–719.
Mader, T.L., Johnson, L.J., Gaughan, J.B., 2010. A comprehensive index for assessing environmental stress in animals. J. Anim. Sci. 88, 2153–2165.
Mount, L.E., Ingram, D.L., 1965. The effect of ambient temperature and air movement on localized sensible heat-loss from the pig. Res. Vet. Sci. 6, 84–90.
Mouttotou, N., Hatchell, F.M., Green, L.E., 1998. Adventitious bursitis of the hock in finishing pigs: prevalence, distribution and association with floor type and foot lesions. Vet. Rec. 142 (5), 109–114.
Mount, L.E., 1975. The assessment of thermal environment in relation to pig production. Livest. Prod. Sci. 2 (4), 381–392.
Møller, J.M., Lund, H., 1995. Design reference Year, DRY. Meddelelse nr 281. Laboratoriet for varmeisolering. Danmarks Tekniske Universitet (in Danish).
Pedersen, P., Jensen, L.T., 2010. Forskellige Gulvtyper Med Og Uden Gulvudsugning Til Slagtesvin I En Sommerperriode. Different Floors With or Without Pit Exhaust for Fattening Pigs in Summer Period (in Danish). Meddelelse Nr. 883. Danish Pig Research Centre.
Rojano, F., Bournet, P., Hassouna, M., Robin, P., Kacira, M., Choi, C.Y., 2016. Computational modelling of thermal and humidity gradients for a naturally ventilated poultry house. Biosys. Eng. 151, 273–285.
Roller, W.L., Goldman, R.F., 1969. Response of swine to acute heat exposure. Trans. ASAE 12 (2), 164–169.
Rong, L., Nielsen, P.V., Bjerg, B., Zhang, G., 2016. Summary of best guidelines and validation of CFD modelling in livestock buildings to ensure prediction quality. Comput. Electron. Agric. 121, 180–190.
Tao, A., Xin, H., 2003. Acute synergistic effects of air temperature, humidity and velocity on homeostasis of market-size broilers. Trans. ASAE 46 (2), 491–497.
Virding, T., 2015. Personal communication/email answer from Ansys Helpdesk, May 7 2015.
Yamamoto, A., Yamamoto, S., Yamagishi, N., Shishido, H., 1989. Effects of environmental temperature and air movement on thermoregulatory responses of lactating cows: an assessment of air movement in terms of effective temperature. Jpn. J. Zootech. Sci. (Jpn.).