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Efficiency of resources of different cooling systems for fattening pigs

A decision support project for the German Ministry of Agriculture was established over the course of two years to investigate the air supply and cooling systems cooling pad, high-pressure evaporation, underfloor air inlet and earth tube heat exchanger on a research farm and under practical conditions on three commercial farms. The project focused on the cooling effect and cost effectiveness of the different systems. The better energy efficiency of the ventilation of the underfloor air supply was due to a lower flow resistance compared with the variants with over floor air supply and especially the earth tube heat exchanger. The cooling pad had the highest cooling efficiency. Water and power consumption for high-pressure evaporation were lower than for the cooling pad, though these parameters are also strongly influenced by the particular controller settings.

Keywords
Cooling systems, cooling pad, high pressure humidifier, underfloor air inlet

Abstract
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A decision support project for the German Ministry of Agriculture was established over the course of two years to investigate the air supply and cooling systems cooling pad, high-pressure evaporation, underfloor air inlet and earth tube heat exchanger on a research farm and under practical conditions on three commercial farms. The project focused on the cooling effect and cost effectiveness of the different systems.

The better energy efficiency of the ventilation of the underfloor air supply was due to a lower flow resistance compared with the variants with over floor air supply and especially the earth tube heat exchanger. The cooling pad had the highest cooling efficiency. Water and power consumption for high-pressure evaporation were lower than for the cooling pad, though these parameters are also strongly influenced by the particular controller settings.

Using suitable equipment to reduce heat stress in pigs due to high housing temperatures is required by the animal protection regulation for production animal husbandry (TierSchNutzV 2009). Water-based systems working on the operating principle of cooling by evaporation and heat exchange systems using airflow through either underfloor systems or pipes installed in the ground are available. The cooling effect and resource efficiency of high-pressure evaporation (HPE), cooling pad, underfloor air inlet and earth tube heat exchanger (ETHE) systems were investigated as part of a decision support project for the German Federal Ministry of Food Agriculture and Consumer Protection (BMELV).

Materials and method

The investigations were conducted on the one hand as in-depth comparative measurements at the research farm (LSZ Boxberg) for the variants underfloor air inlet, high-pressure evaporation and cooling pad, compared with a reference compartment without additional cooling (**Table 1**). On the other hand flanking measurements with a reduced scope were carried out on three working farms with an underfloor air inlet, ribbed pipe earth-tube heat exchanger or high-pressure evaporation (**Table 2**). These variants also differed with regard to air supply (underfloor, porous ceiling or high-velocity ventilation).

The main focus of the investigations was at the research farm. In a pig fattening unit with forced ventilation, four identically built compartments each with six boxes were equipped with the necessary measuring equipment. The compartments had fully slatted floors and sensor-controlled liquid feeding. Each compartment housed 125 animals (20 to 22 animals per pen), providing 1.0 to 1.10 m² space per animal. Animals left the housing as of a final weight of 115 kg. Different air supply and cooling variants were compared in the four test compartments (**Table 1**).

The three working farms (**Table 2**) were also fattening units with forced ventilation and slatted floors. The farms with high-pressure evaporation (HPE) and underfloor air inlet cooling had fully slatted floors while the farm with an earth tube heat exchanger (ETHE) had a half-slatted floor. Liquid feeding was

Table 1

Air supply and air cooling variants on the research farm

	Referenz (ohne Kühlung) ***Reference (without cooling)***	**Unterflurzuluft** ***Underfloor air inlet***	**Hochdruckbefeuchtung** ***High pressure evaporation***	**Kühlpad** ***Cooling pad***
Zuluft *Air supply*	von außen über Dachraum und Porendecke *from outside through the attic and porous ceiling*	von außen über zentralen Unterflurkanal mit Lufteintritt unterflur in Versorgungsgang des Abteiles und Überströmung der Buchtenabtrennungen *from outside through the underfloor channel to the compartment and over the box partitions*	von außen über Dachraum und Porendecke *from outside through the attic and porous ceiling*	an Stirnseite des Stallgebäudes über Kühlpad (Flächenkühler auf Wasserbasis), dann über Dachraum und Porendecke *from frontside of the pig houses through the cooling pad via attic and porous ceiling*
Abluft *Exhaust air*	1 dezentraler Messventilator *1 local measuring fan*	1 dezentraler Messventilator *1 local measuring fan*	1 dezentraler Messventilator *1 local measuring fan*	1 dezentraler Messventilator *1 local measuring fan*
Kühlung *Cooling*	ohne *without*	Wärmetausch an Unterflurkanalwänden *heat exchange at the walls of the underfloor channel*	Hochdruckbefeuchtung der Stallluft (ggf. auch zur Befeuchtung im Winter) *high pressure evaporative indoor air cooling (also for humidifying use in winter)*	Befeuchtung der Zuluft (nur bei Außentemperatur > 24 °C) *humidifying the inlet air (only at outdoor temperature > 24 °C)*
Heizung *Heater*	Deltarohre unter der Porendecke *Delta tubes below porous ceiling*	Wärmetausch an Unterflurkanalwänden *heat exchange at the walls of the underfloor channel*	Deltarohre unter der Porendecke *Delta tubes below porous ceiling*	Deltarohre unter der Porendecke *Delta tubes below porous ceiling*

used on the farm with underfloor air inlets, while mash was fed on the farms with HPE and ETHE. The number of animals per compartment ranged between 74 and 306. The space available per animal was between 0.75 and 0.85 m².

The parameters measured were temperature, humidity, differential pressure and airflow rate along with energy and water consumption. The housing climate parameters were recorded at least once per minute using Ahlborn measurement logging instruments. Consumption data were recorded via meter modules (power and water meters) using Wago data logging instruments. These two data logging systems were networked to a central computer where all raw data came together and were saved.

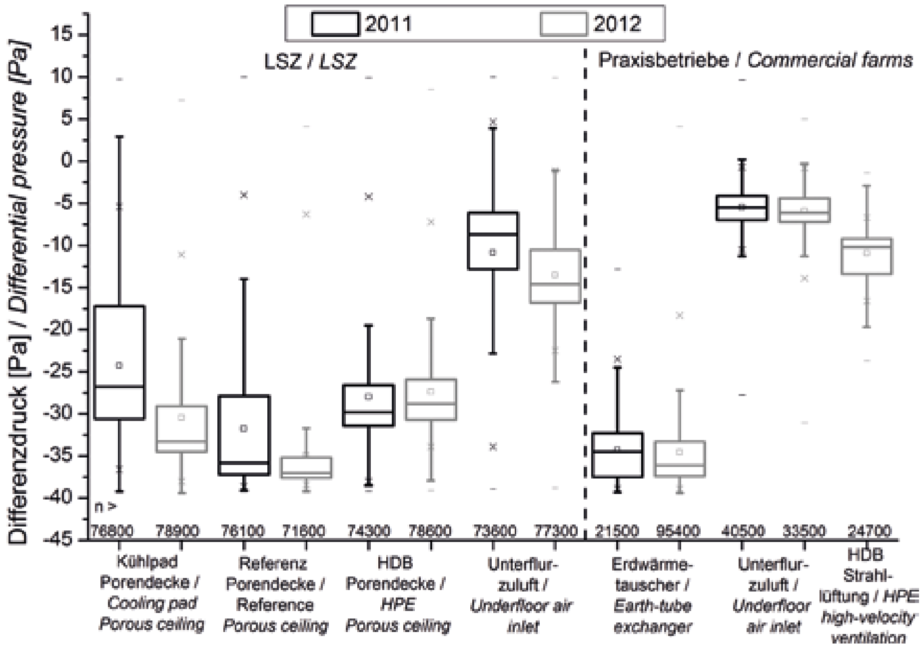
Measurements were logged at the research farm from January 2011 to September 2012. Consumption data were recorded up to December 2012. The measurement period on the working farms was between July 2011 and September 2012. There were, however, frequent gaps in the consumption measurements, so that only a limited comparative data analysis of the selected pa-

Tabl 2

Air supply and air cooling variants on the working farms

	Unterflurzuluft ***Underfloor air inlet***	**Hochdruckbefeuchtung** ***High pressure evaporation***	**Erdwärmetauscher** ***Earth-tube heat exchanger***
Zuluft *Air supply*	von außen über zentralen Unterflurkanal mit Lufteintritt unterflur in Versorgungsgang des Abteils und Überströmung der Buchtenabtrennungen *from outside through the underfloor channel to the compartment and over the box partitions*	von außen über Dachraum und Zuluftventile (Strahllüftung) *from outside through the attic and air inlets (high velocity ventilation)*	von außen über Rippenrohre zum Unterflurkanal mit Lufteintritt in Versorgungsgang des Abteils und Überströmung der Buchtenabtrennung *from outside through the ribbed pipes to the underfloor channel and then to the compartment and over the box partitions*
Abluft *Exhaust air*	2 dezentrale Messventilatoren *2 local measuring fans*	4 dezentrale Messventilatoren *4 local measuring fans*	1 dezentraler Messventilator *1 local measuring fan*
Kühlung *Cooling*	Wärmetausch an Unterflurkanalwänden *heat exchange at the walls of the underfloor channel*	Hochdruckbefeuchtung der Stallluft (ggf. auch zur Befeuchtung im Winter) *high pressure evaporative indoor air cooling (also for humidifying use in winter)*	Wärmetausch an Rippenrohren und Erdreich *heat exchange through ribbed pipes and soil*
Heizung *Heater*	Wärmetausch an Unterflurkanalwänden *heat exchange at the walls of the underfloor channel*	Gaskanone *gas heater (gas blower)*	Wärmetausch an Rippenrohren und Erdreich *heat exchange through ribbed pipes and soil*
Tierzahl pro Abteil *Animals per compartment*	90	306	74

Fig. 1



Differential room pressure at an outdoor temperature > 22 °C on the research farm Landesanstalt für Schweinezucht Boxberg (LSZ) and the working farms in the years 2011 and 2012 (HPE = high-pressure evaporation)

rameters was possible. For this reason the results for resource efficiency and cooling effect in the following can only be shown with regard to the comparative measurements at the research farm.

Results

Differential Pressure

The type of air supply (**Tables 1** and **2**) was responsible for a systemic difference, which was only indirectly related to the type of cooling system. The largest differences in differential pressure in the compartment between the variants with porous ceiling ventilation, underfloor airflow, earth tube heat exchanger and high-velocity ventilation were measured in summer due to the high airflow rate required at that time. The greatest negative pressure was measured in the working farm compartments with ETHE and in the research farm compartments with porous ceilings at an outdoor temperature of over 22 °C (**Figure 1**). The negative pressure was lower with air supply through an underfloor air inlet (research farm and working farm) and high-velocity ventilation (working farm with HPE).

The difference in differential pressure between the two underfloor air inlet systems (research farm and working farm), however, was a result of differing air supply route designs. On the working farm with underfloor ventilation the supply air flows directly from outside without re-routing through the underfloor channel. As regards the underfloor air inlet on the research farm, Adrion et al. [1] already showed that a pipe in the underfloor channel obstructed the flow of supply air, which then led to increased negative pressure in the compartment.

In addition, in a comparison of the compartments with porous ceilings on the research farm it was established that the airflow through the cooling pad itself did not present any significant additional flow resistance for the supply air. The large divergence in measurements in the cooling pad compartment is due to the introduction of young animals in summer. During this period, although the outdoor temperature was around 1 to 2 Kelvin above 22 °C, the set temperature for the young animals in the compartment was 25 °C. This resulted in very low airflow rates. Measurements higher than 0 Pascal came about especially with low airflow rates due to outside air flowing past the differential pressure hoses. As this occurred at all measuring points, the measurement data were not adjusted.

The air supply pipes of the ETHE on the working farm caused the greatest air flow resistance. Thus the average differential pressure (measured at AT > 22°C) at the end of the ribbed pipes at the transfer to the central air supply channel was about -34 Pa. Only a small change to around -36 Pa was measured from there to the compartment. This small difference in pressure meant that incorrect ventilation could occur. On warm days, if 10 to 12 of the 14 fans (14 compartments) were being operated at 100 % speed, it was possible for air in the other 2 to 4 compartments with lower fan speeds to be wrongly aspirated into the exhaust air stack instead of the ribbed pipes. To avoid this, fan speed had to be set to at least 40 %. For this reason, the farm manager selected a minimum fan speed of 60 % in the affected compartments on warm days.

Power consumption for ventilation

The differences in air supply shown above also had an effect on the fan power consumption. Identical exhaust fans are installed in every compartment on the research farm so that power consumption can be compared directly (**Table 3**).

Table 3

Airflow rate and cost of power at the research farm Landesanstalt für Schweinezucht (LSZ Boxberg)

LSZ Boxberg	Zeitraum *Period*	Referenz *Reference*	Unterflurzuluft *Underfloor air inlet*	Hochdruckbefeuchtung *High pressure evaporation*	Kühlpad *Cooling pad*
Ø Luftvolumenstrom [$m^3 h^{-1}$] *Airflow rate [$m^3 h^{-1}$]*	2011	3765	4245	3623	3413
	Jan.–Sept. 2012	4686	4841	4239	3995
Stromverbrauch [kWh] *Power consumption [kWh]*	2011	1193	871	1375	1210
	2012	1699	923	1742	1527
Stromkosten[1)] je TP und Jahr [€ $TP^{-1} a^{-1}$]/ *Cost of power[1)] per animal place and year [€ $AP^{-1} a^{-1}$]*	2011	1.81	1.33	2.09	1.84
	2012	2.53	1.40	2.65	2.32

TP: Tierplatz/*AP: Animal place.*

1) Annahme 0,19 € kWh^{-1}/*Assumption 0,19 € kWh^{-1}.*

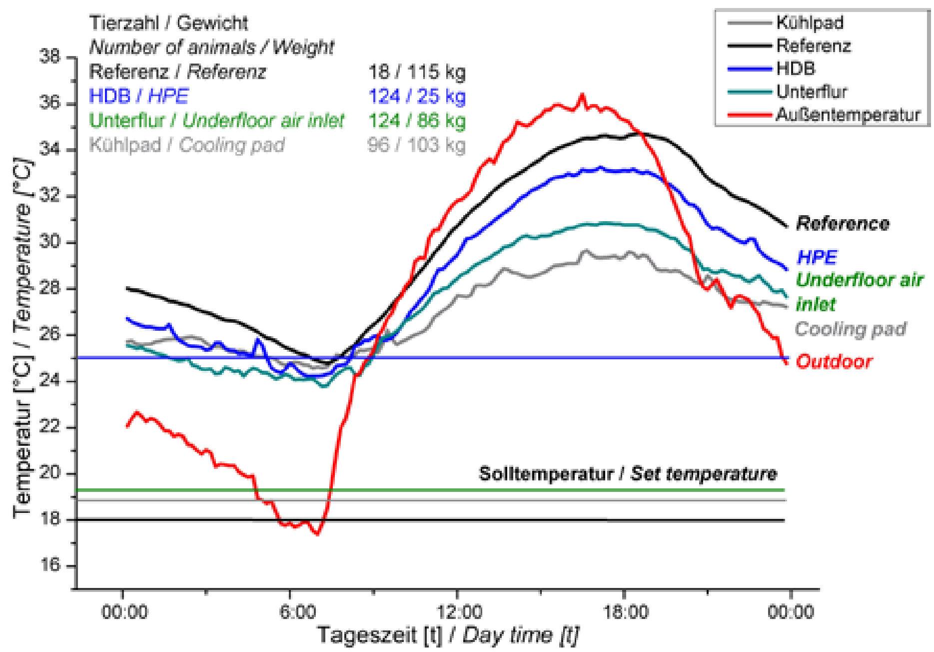
The comparative study on the research farm in 2012 showed higher power consumption due to the higher temperatures that year and the resulting longer time components with high airflow rates. In the underfloor air inlet compartment, less power was used for ventilation over the entire investigation period. This is attributable to the low negative pressure in that compartment (**Figure 1**). At the same time, the airflow rate here is higher than in the compartments with porous ceilings (reference, HPE, cooling pad). Van Caenegem and Didier [2] and Van Caenegem et al. [3] describe high power consumption for ventilation in housing with an ETHE. This is due to higher air flow resistance in the ribbed pipes.

Power and water consumption of the cooling systems

A determining factor in a evaluating the cost-effectiveness of a cooling system is power and water consumption data. These must be assessed with regard to cooling performance in each case.

The HPE at LSZ Boxberg used 10 034 l water and 189.4 kWh power in 2011. In the following year the figures were 5 742 l

Fig. 2



Temperature curves on the research farm Landesanstalt für Schweinezucht Boxberg (LSZ) on a hot day water and 159.3 kWh power. The lower water consumption in 2012 was attributable to frequently blocked nozzles. The nozzles clogged up, preventing water spraying, although the pump was in operation and consuming power. Nozzle cleaning or replacement was not always carried out on time and involved additional work. The cooling pad used 2 2941 l water and 393.6 kWh power in 2011, followed by 16 233 l water and 174.1 kWh power in 2012. In 2012, power and water consumption were reduced significantly thanks to improved control settings for the cooling pad. In contrast to the preceding year, cooling then shut down when relative humidity in the compartment rose above 80 %. In addition, in 2012 the cooling pad was only activated when the outdoor temperature was over 24 °C instead of 22 °C.

Cooling effect and performance

The cooling effect and cooling performance of the water-based systems by comparison with the underfloor air inlet system are examined more closely below for the variants on the research farm. In summer 2012 an average outdoor temperature of 25.44 °C was measured over a 74 day period for the temperature category "Outdoor temperature above 22 °C". This was thus 0.71 K higher than in 2011 with an average outdoor temperature of 24.73 °C over 82 days for the same evaluation category. On warm days the median, average and maximum compartment temperature levels of the cooled variants were lower than in the reference systems without cooling over the entire measuring period. Average cooling by the underfloor air supply was around 3.5 K, while the cooling pad provided a temperature reduction of on average around 5 K. As shown in **Figure 2**, all cooling variants were able to alleviate temperature spikes on the warmest day of the investigation period in August 2012, with maximum daytime temperatures of 36 °C: HPE by 3.2 K; underfloor air inlet by 5.4 K; cooling pad by 7 K. Differing housing occupation levels and temperature settings should also be taken into account here.

The performance of the individual systems can be calculated as the enthalpy change of the air via the temperature changes measured in the supply air from outdoors into the compartment. This is equivalent to the amount of energy [kWh] released from the supply air and was calculated using equation 1 [4; 5].

$$\dot{Q} = \dot{m}_1 \cdot c_p \cdot (\vartheta_2 - \vartheta_1) \qquad \text{(Eq. 1)}$$

$\dot{Q}$	[kWh]	heat flow
$\dot{m}_1$	[kg h^{-1}]	air supply flow
c_p	[kWh (kg K)$^{-1}$]	specific heat of the air
ϑ	[°C]	temperature

Equation 2 was used to calculate the theoretical cooling performance of the high-pressure evaporation [6], as the HPE unit is located in the compartment so that at the same time the compartment temperature is also influenced by the animals. This cannot be taken into account in equation 1. In equation 2 the evaporation energy of water is used to calculate the cooling performance of the high-pressure evaporation. The result is multiplied by the amount of water consumed.

$$Q_V = 2500{,}8 - 2{,}372 \cdot t \qquad \text{(Eq. 2)}$$

Q_V	[kJ kg^{-1}]	evaporative heat of water
t	[°C]	water temperature
2 500,8	[J kg^{-1}]	evaporative heat of water at 0 °C

Calculations were made only for the period from April to September in 2011 and 2012. All calculations were based on the assumption that the water temperature was 15 °C and 100 % of the water consumed also evaporated. It was possible to calculate the evaporative energy for both the high-pressure evaporation and the cooling pad. In addition, in the case of the cooling pad it was also possible to calculate the temperature differential between the warm supply air and the cooled air. This produced two results for determining the cooling performance. For the underfloor air inlet, the cooling performance could only be ascertained by calculating the temperature differential. It is clear from **Table 4** that there are considerable differences between the two calculation methods. However, the performance of the cooling pad is better than that of the other systems regardless of the method of calculation. In 2012 particularly, the cooling performance was more than double to three times higher than cooling with high-pressure evaporation or the underfloor air inlet.

Table 4

Energy efficiency of the different cooling systems

Jahr *Year*	Verdunstungsenergie des verbrauchten Wassers [kWh] *Evaporation energy of the consumed water [kWh]*		Abgabe der Wärmemenge zum Erlangen der Temperaturdifferenz ΔT [kWh] *Heat emission to achieve the difference in temperature ΔT [kWh]*	
	Hochdruckbefeuchtung *High pressure evaporation*	Kühlpad *Cooling pad*	Kühlpad *Cooling pad*	Unterflur *Underfloor air inlet*
2011	6 871	15 710	6 547	2 712
2012	3 925	11 116	8 040	3 234

Conclusion

The study showed that the type of air flow – and in particular the airflow resistance inherent to the type of air supply – has considerable influence on the differential pressure in the compartment and thus on the fan power consumption. Running costs are also a point of interest with regard to the cooling systems. Water and power consumption for the cooling pad pump are higher than for HPE, but the cooling pad performs better. In the case of the underfloor air inlet there are no costs on top of running the animal housing other than the additional building costs. Various scenario analyses from a cost-effectiveness review for the comparative study at LSZ Boxberg have shown, for example, that the different cooling variants would have to compensate for a decrease in daily weight gain of between 25 and 40 g over a summer fattening cycle to cover the extra costs incurred by the cooling systems. The advantages of using the underfloor air inlet for heating purposes in winter and related savings in heating costs have not been taken into account in this calculation.

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