METHODS FOR EVALUATION OF THE THERMAL ENVIRONMENT IN THE ANIMAL-OCCUPIED ZONE FOR WEANED PIGLETS

A. V. van Wagenberg, J. H. M. Metz, L. A. den Hartog

ABSTRACT. *Two evaluation methods are introduced for expression of the quality of the thermal conditions in the animal-occupied zone (AOZ) in rooms for weaned piglets. One method uses only the AOZ temperature, while the other uses the kata-value (KV), which combines air velocity and temperature and indicates the heat loss to the environment. AOZ thermal conditions should be within the thermo-neutral zone (TNZ) of the piglets. The methods use two new numerical indicators, based on the duration and the magnitude of excess of AOZ thermal conditions outside the TNZ: one referring to the number of degree-hours (°Ch), and the other to the number of kata-value-hours (KVh) during a batch. The objective was to evaluate the two methods in a door-ventilated room for weaned piglets. In the experiment, temperature was measured in all ten pens of a room and air velocity in three pens during eight successive batches, together lasting about one year. Pens closer to the air inlet had higher temperatures and lower KV than pens in the back of the room. Momentary temperature difference between pens reached up to 7°C. During the first days of most batches, pen conditions in the back of the room were "too cold." At the end of most batches, pen conditions in the middle of the room were "too warm." The value of the two indicators varied per pen and per batch from 0 to 319°Ch (0 to 219 KVh) "too cold" and from 0 to 602°Ch (0 to 793 KVh) "too warm." For "too warm" conditions, there was a significant ($P < 0.001$) and strong correlation between the two indicators ($R^2 > 0.96$), but not for "too cold" conditions ($R^2 > 0.48$). Therefore, measuring air velocity in addition to temperature in the AOZ for recognition of "too cold" conditions had surplus value. Excluding outliers from one extremely warm batch, the maximum value of the indicator for "too warm" was 65°Ch. This indicator significantly affected the feed conversion ratio, which increased with 0.0024 kg/kg per °Ch, and daily growth and daily feed intake, which decreased with 0.0022 kg/animal and 0.0030 kg/animal, respectively, per °Ch. The methods presented are useful tools in the technical evaluation of climate systems and for a more optimal climate control in the AOZ.*

Keywords. *Animal-occupied zone, Door-ventilated pig room, Kata-value, Weaned piglet, Temperature, Thermo-neutral zone.*

The climatic environment of animals is an important aspect in livestock production, especially for weaned piglets. Directly after weaning, piglets are subjected to many stresses, including being separated from the sow, being moved to a new and different environment, and changing from milk to a solid diet (Le Dividich and Herpin, 1994; McCracken et al., 1995). A widely accepted range for the optimal thermal conditions of the piglet is defined as the thermo-neutral zone (TNZ), which is the range of thermal environments with minimal metabolic rate (Van 't Klooster et al., 1989; CIGR, 1999, 2002; Quiniou et al., 2000; Van Ouwerkerk, 2000). The limits of the TNZ are mostly expressed in air temperature, but air velocity is considered as an important factor too, as it is a component of the convective heat loss and thus the thermal comfort (Le Dividich and Herpin, 1994; Tao and Xin, 2003). This heat loss is indicated in the kata-value (KV), which combines air temperature and air velocity, and was previously used in pig rooms by Scheepens et al. (1991) and Lambers and Van der Wolf (1996). Models have been developed that calculate the theoretical limits of the TNZ (Bruce and Clark, 1979; Van Ouwerkerk, 2000), either expressed in air temperature or in KV. When the thermal environment of the piglet exceeds the limits of the TNZ, animal performance (feed intake, growth, feed conversion ratio) is expected to deteriorate (Van 't Klooster et al., 1989; Quiniou et al., 2000; Van Ouwerkerk, 2000) with an increased risk for animal health under certain circumstances. This has been confirmed in studies where pigs were placed in experimental climate chambers and exposed to an adverse thermal environment outside the TNZ, such as high temperatures and low air temperature in combination with a high air velocity (Verhagen et al., 1987; Scheepens et al., 1991; Herpin and Lefaucheur, 1992; Nienaber et al., 1996; Collin et al., 2002).

The problem is that there is no established method to indicate the quality of the thermal environment of a piglet during a batch (i.e., one group of piglets managed all-in/all-out in a specific room) regarding the time course of temperature and/or KV. Batch average values of temperature or KV are not suitable because excessively cold moments compensate for excessively warm moments in the averages. Furthermore, the climatic demands of the piglets (the limits of the TNZ) change over time during the batch; for example, the desired temperature at the beginning of a batch is too warm for later in the batch. A further complication is that KV

Article was submitted for review in April 2005; approved for publication by Structures & Environment Division of ASABE in September 2005.

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  ISSN 0001−2351

gives better insight into the thermal environment than air temperature alone, but measuring air velocity requires expensive and vulnerable equipment (Van Wagenberg and de Leeuw, 2003). Therefore, the need for measuring air velocity in addition to air temperature should be argued.

Another aspect of climate optimization in pig rooms is the spatial gradients of climate factors. Pig rooms are commonly equipped with heating and ventilation systems to maintain the right indoor air quality and thermal environment. These systems are generally controlled based on room climate, using one or more temperature sensors somewhere in the room. But, within a ventilated pig room, the thermal environment (air temperature, air velocity) will depend on the location within the room (Randall, 1980; Van 't Klooster, 1994; Hoff, 1995; Van Wagenberg and Smolders, 2003; Van Wagenberg et al., 2005). An obvious example is a door-ventilated room where fresh air enters the room through the door opening with a maximum air velocity of about 1 m/s. Via the operator walkway, the air flows over the solid pen partitions into the pens. In this common Dutch system, it is known that air distribution over the pens is not homogeneous, resulting in differences in thermal environment between pens (Van Wagenberg and Smolders, 2003; Van Wagenberg and de Leeuw, 2003; Van Wagenberg et al., 2004). When evaluating heating and ventilation systems, the thermal conditions in the region around the pigs, called the animal-occupied zone (AOZ), are of most concern (Heber et al., 2001, Zhang et al., 2001). This heterogeneity in the room and heterogeneity within the AOZ should be taken into account for providing optimal climatic conditions to the animals.

In this study, two evaluation methods are introduced that express the quality of the thermal environment of weaned piglets in the AOZ by numerical indicators, using existing knowledge about the limits of the TNZ of the piglets. The first method takes into account the temperature; the second is based on KV in the AOZ. The number of hours that the AOZ thermal conditions exceed the limits of the TNZ, as well as the magnitude of the excess, is calculated. The objective of this study was to apply the two methods in a door-ventilated room and to compare their potential value for AOZ climate evaluation and control for weaned piglets. Thereby, the relationship between both indicators is investigated as well as the effect on the piglet performance when the climate exceeded the limits of the calculated TNZ.

Material and Methods

Kata-Value

The kata-value (KV) indicates the heat loss of warm (skin) surfaces like those of pigs. The relation between KV, air temperature (T, °C), and air velocity (U, m/s) was empirically determined by calculating the heat loss from the measured time span for cooling a silver-coated glass bulb filled with alcohol from 38° to 35°C. It yielded (Crauwels et al., 1991):

$$\text{KV} = (36.5\text{°C} - T) \cdot \left(1.07 + 1.73\sqrt{U}\right) \tag{1}$$

where KV is expressed in mW/cm^2. KV increases when the conditions get colder. Physical analysis of the heat transfer coefficient in this formula $(1.07 + 1.73\sqrt{U})$ reveals that the first term (1.07) indicates heat transfer independent of air velocity (radiation, natural convection), and the other term indicates forced convection. For laminar flow, the heat transfer coefficient is, as generally found in literature, proportional to $\sqrt{U}$ ($\sim \sqrt{\text{Reynolds}}$) (Kreith, 1976). Figure 1 shows KV for various temperature and air velocity combinations.

At an air temperature of 20°C and air velocity of 0.01 m/s (point *a* in fig. 1), KV is 20.5. When the air velocity is 0.19 m/s at the same air temperature, KV is 30.1 (point *b* in fig. 1), indicating a 50% higher sensible heat loss. Because the contact surface between a weaned piglet and the air varies from 1000 to 3000 cm^2 as the piglet grows from 8 kg to up to 23 kg (Van Ouwerkerk, 2000), KV of 30 reflects sensible heat losses between 30 to 90 W per piglet.

Thermo-Neutral Zone of Weaned Piglets

For calculation of the TNZ limits for both temperature and KV, the simulation software ANIPRO (Van Ouwerkerk, 2000) was used. ANIPRO is based on earlier detailed studies on thermal comfort of pigs (Bruce and Clark, 1979; Sterrenburg and Van Ouwerkerk, 1986a, 1986b). The conditions used as input for ANIPRO were based on the average situation in the experimental room: the piglets were weaned and moved directly to the experimental room, where they grew from 8 to 23 kg in about 35 days; there was a solid insulated floor; floor heating was on during the first eight days; and surfaces for radiation heat losses (wall, roof, pen partitions) had the same temperature as the air. Total feed intake increased almost linearly from 0.1 kg per day on day 0 to 1.1 kg per day on day 35. The energy content of the feed

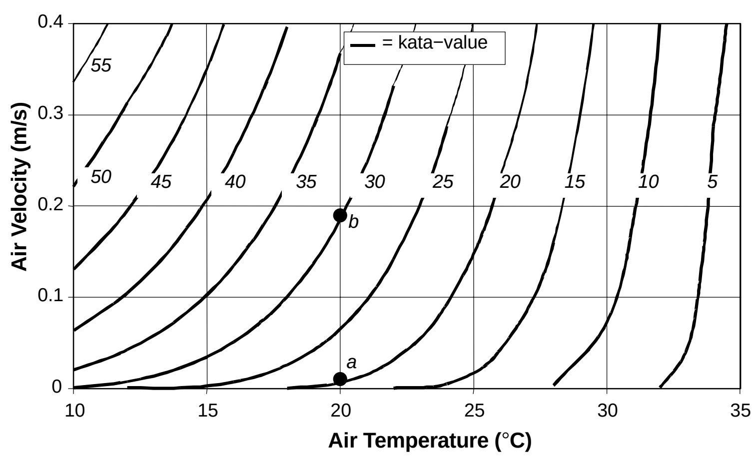

Figure 1. Range of kata-values calculated for various temperature and air velocity combinations (*a* and *b* are reference points in the text).

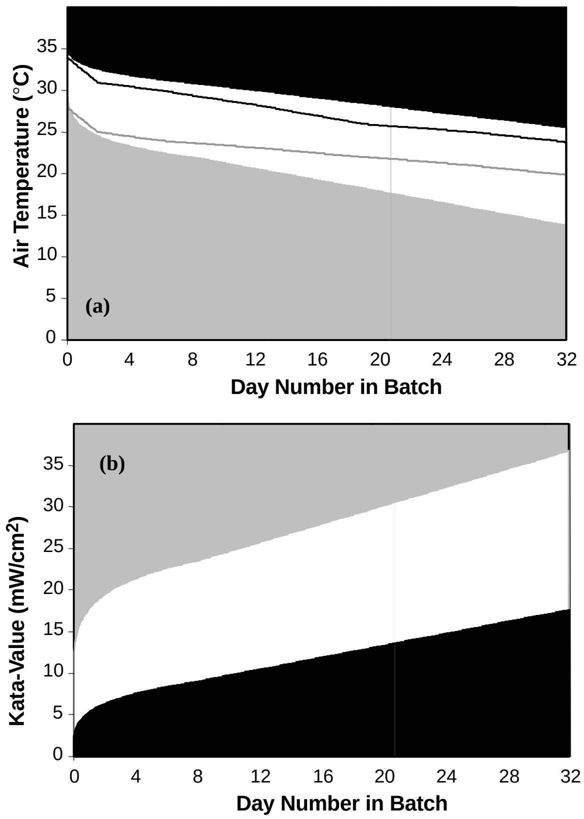

Figure 2. Thermo-neutral zone (white area) expressed in terms of (a) temperature and (b) kata-value for weaned piglets (gray area = "too cold," black area = "too warm") and including the climatic settings (gray line is setpoint for room heating, and black line indicates the temperature with maximum ventilation in the room).

was based on the diet used in the experiment and is described in the next section. The limits calculated are given in figure 2; the temperature zones calculated are based on a constant air velocity of 0.10 m/s.

The TNZ limits as shown in figure 2 were used in the evaluation methods, thereby ignoring differences in TNZ limits between pens due to possible differences in animal performance between pens. The course of AOZ thermal conditions was compared with the TNZ limits. The cumulative excess was determined using the duration and magnitude of the excess of the TNZ limits and is expressed in the number of degree-hours (°Ch, method 1) or kata-value-hours (KVh, method 2) outside the TNZ per batch. An excess of the TNZ limits by 1°C for 2 h, or by 2°C for 1 h, resulted in a cumulative excess of 2°Ch, and so on. The degree-hours method was used before in model simulations to quantify heating or cooling requirements in finishing pig rooms, but spatial gradients and the relation with TNZ limits were ignored (Panagakis and Axaopoulos, 2004).

Periods with an excess of the lower limit of the TNZ expressed in temperature, and an excess of the upper limit of the TNZ expressed in KV, are defined as "too cold" in this article. Periods with an excess on the opposite side of the TNZ are defined as "too warm."

Experiment

Housing System and Animals

The experiment was carried out in a door-ventilated room for weaned piglets at the experimental pig farm of the Animal Sciences Group in Raalte, The Netherlands, in the period from 10 May 2002 to 12 June 2003. The room was operated according to the "all-in/all-out" principle. In total, 720 piglets were used in the study, distributed over eight batches. Male piglets were castrated. The piglets were weaned at four weeks and divided into groups of nine piglets per pen. The piglets from the same sow were distributed over different pens as much as possible. The aim was to have 4 (or 5) barrows and 5 (or 4) gilts per pen, with an average weight between 8 and 9 kg. Piglets weighing less than 5 kg or more than 11 kg were excluded. The piglets received feed and drink water *ab libitum*. Feed was provided by dry feeders. In the first two days after weaning, they received creep feed (11.79 MJ NE). In the next three days, they were gradually switched over to a pre-starter diet (9.3 MJ NE, 10.1 g/kg lysine), which was fed until day 7 after weaning. Then, from day 8 until day 10 after weaning, the piglets were gradually switched over to a starter diet (9.5 MJ NE, 10.1 g/kg lysine), which was fed until the end of the rearing period. Most batches ended after 32 days; exceptions included batch 4 with 28 days, and batches 6 and 8 with 39 days.

Description of the Room

Figure 3 shows a plan view and cross-section of the experimental door-ventilated room. The internal walls of the building were not insulated, and the central alley functioned as a common air inlet for the rooms on both sides. Fresh air was preheated in the central alley to a minimum of 5°C when the outside temperature was lower. The right side of the experimental room bordered the relatively cold central alley; the left side bordered another warm room. In the experimental room were ten pens, for nine piglets each, five pens on each side of the central operator walkway. As seen from the walkway, in the front of the pens was a metal slatted floor above the water channel (which was filled with a layer of water in the beginning of the batch and was designed to collect small amounts of manure and urine produced in the front of the pen), followed by a solid concrete floor with a spherical shape and with floor heating, and in the back of the pens was a metal slatted floor above the manure channel. No bedding material was used in the pens. Room air heating was available via water-filled heating pipes on both sides of the room and a radiator in the back of the operator walkway. Ventilation air entered the room through an opening in the door and flowed over the operator walkway to the back of the room. Air was removed from the room by a ventilator in a circular ventilation shaft just behind the door at 2.1 m height. To measure the ventilation rate, a two-blade ventilation rate sensor (accuracy <50 m^3 h^{-1}, Fancom BV, Panningen, The Netherlands) was mounted in the ventilation shaft (Berckmans et al., 1991). Additionally, to control the volumetric airflow rate, an automatic valve was mounted in the ventilation shaft. A detailed description of the experimental room is given by Van Wagenberg and de Leeuw (2003) and Van Wagenberg et al. (2004).

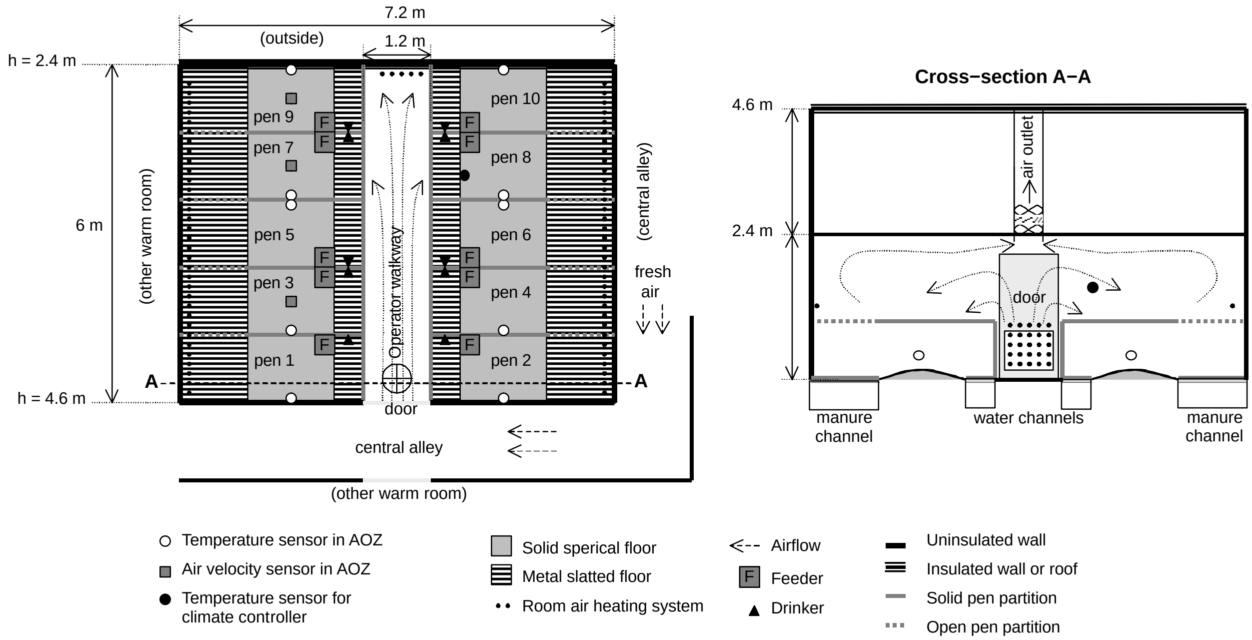

Figure 3. Plan and cross-section of compartment with numbered pens (h = height in the room).

Table 1. Temperature setpoints in the experimental room for room heating, floor heating, and ventilation, and the minimum and maximum ventilation.[a]

	Temperature Setpoint (°C)			Ventilation per Piglet (m^3/h)[a]	
Day	Room Heating	Floor Heating	Ventilation[a]	Minimum	Maximum
2	28	40	30	4	10
4	25	40	27	4	11
8	24	35	26	5	13
21	18	25	21	5	20
28	18	25	21	6	25
49	17	20	20	6	25

[a] Setpoint indicates lower end of p-band (temperature range between minimum and maximum ventilation), p-band was 4°C.

Control of heating and ventilation was based on one room temperature measurement at 1.5 m height above pen 8 (fig. 3). Table 1 shows the climate computer settings used. The setpoint for room heating (second column in table 1) and the temperature where the maximum ventilation was reached (4˚C above the stated setpoint for ventilation, fourth column in table 1) are also plotted in figure 2 to illustrate that climate settings were such that the room air heating switched on before the lower limit of the TNZ was reached and that maximum ventilation capacity was used as soon as room temperature reached the upper limit of TNZ.

Measurements and Recordings

In all pens, air temperature in the AOZ was measured at one point at about 0.15 m height, 1 m from the front pen partition (halfway point of the solid floor) and about 0.05 m from the side pen partition at the opposite side of the feeder by using Pt100 sensors (accuracy 0.1˚C). To protect the sensors from manipulation by the piglets, they were placed in cages (0.09 m depth, 0.14 m width, and 0.22 m height) made of 6 mm diameter iron wire and with a mesh width of 25 × 25 mm. Momentary temperature values were logged with an interval of 600 s. Air velocity was measured in pens 3, 7, and 9. These pens were chosen because they were on one side of the operator walkway and distributed over the depth of the room to give insight into the differences in AOZ climate between pens. Ultrasonic anemometers (Windmaster 1086M, Gill Instruments Ltd., Lymington, U.K.) were used at 0.3 m height, 1 m from the front pen partition and 0.6 m from the side pen partition. Based on earlier research (Van Wagenberg and de Leeuw, 2003), the measuring frequency was set at 1 Hz and the logging interval was 300 s. The accuracy was 0.01 m/s. The measuring system used is described in detail by Van Wagenberg and de Leeuw (2003). Temperature of the inlet air (at 0.2 m height in the door opening) was measured (Pt100 sensor, accuracy 0.1˚C) and recorded every 600 s.

Animal performance was measured by weighing each piglet on day 0, on day 18, and at the end of the batch. On day 18 and at the end of the batch, the total feed supply per pen over the preceding period was registered. The data were used to calculate the average daily growth per piglet (individual) and per pen (pen average), the pen average daily feed intake per piglet, and the pen average feed conversion ratio. In case of culling, the body weight of the culled piglet was measured to estimate the amount of feed that was consumed by this individual piglet. These piglets were not used for calculating average animal performance (in total, 29 piglets were culled).

Data Analysis

Kata-value was calculated based on hourly average values of the temperature and air velocity. The course of the temperature in all ten pens and the course of KV in three pens were analyzed and compared with the calculated limits of the TNZ. The cumulative excess of the TNZ limits in ˚Ch and KVh was determined per pen and per batch separated for days 0 to 18 and for day 18 to end of batch. The cumulative excesses in ˚Ch and in KVh were compared with a linear regression analysis (Genstat, 1993) in order to derive the surplus value of measuring air velocity.

The ANOVA procedure in Genstat (1993) was used to determine if there were significant differences in animal performance between pens. The effect of cumulative excess in °Ch and in KVh on animal performance was examined separately for days 0 to 18 and for day 18 to end using the statistical model (Genstat, 1993):

$$Y = constant + starting\ weight + X + e \qquad (2)$$

where *Y* is the pen average daily feed intake per piglet, the pen average feed conversion ratio, and the pen average daily growth per piglet; *X* is the cumulative excess of TNZ limits (in both °Ch and KVh); and *e* is the error term. The *starting weight* was the average body weight per pen on day 0 or on day 18. The same model was also used to analyze the individual growth per piglet per day (*Y*), in which case the *starting weight* was the individual weight per piglet.

In the analysis of pen average piglet performance, data records were ignored when the pen average body weight was less than 18 kg at the end of the batch. In the analysis of individual piglet data, data records were ignored if piglet weight at the end of the batch was below 16 kg. The reason for this is that the calculated TNZ limits would not be representative for these slow-growing animals, and therefore the calculated cumulative excess would not be representative. In analysis of pen averages, data were also ignored when two or more animals were culled in a pen during one batch, because this would diminish the reliability of the pen data. Furthermore, when the cumulative excess of TNZ limits during one batch was extremely high compared to the other experimental batches, those data were ignored to eliminate the disturbing effect of those outliers in the Genstat analysis. The applied statistical model will not be useable for accidental extreme cold or warm batches.

Results

Temperature and Air Velocity Measurements and Calculated Kata-Value

In figure 4, the hour-average temperatures and air velocities as measured in pen 9 during all eight batches (more than 7,000 hourly averages) are plotted versus each other and versus KV. The distribution of the data points as measured in pen 9 was also representative for pens 3 and pen 7 (not shown). The only difference was that in pen 9 the conditions were often colder, the temperatures measured lower and air velocities higher, resulting in higher KV.

Figure 4a shows that air velocity varied from 0.03 to 0.25 m/s, almost independently of the temperature (R^2 = 0.030). At temperatures above 25°C, the air velocity hardly reached above 0.15 m/s. At all air velocities, there was much variation in KV, and as expected, KV was on average somewhat higher at higher air velocities (fig. 4b). Comparison of figures 4b and 4c shows that the relationship of KV with temperature (R^2 = 0.86) is stronger than with air velocity (R^2 = 0.27). At lower temperatures, there was some variation in KV, while at higher temperatures, the variation in KV became smaller and temperature appeared to be a good predictor for KV. Figure 4 indicates that air temperature was the most determinant factor for KV under the experimental conditions.

In almost all pens and during all batches, "too cold" moments only occurred during the first 18 days of the batch, and "too warm" moments only after day 18 (data not shown). Figure 5 shows examples of the course of the temperature and

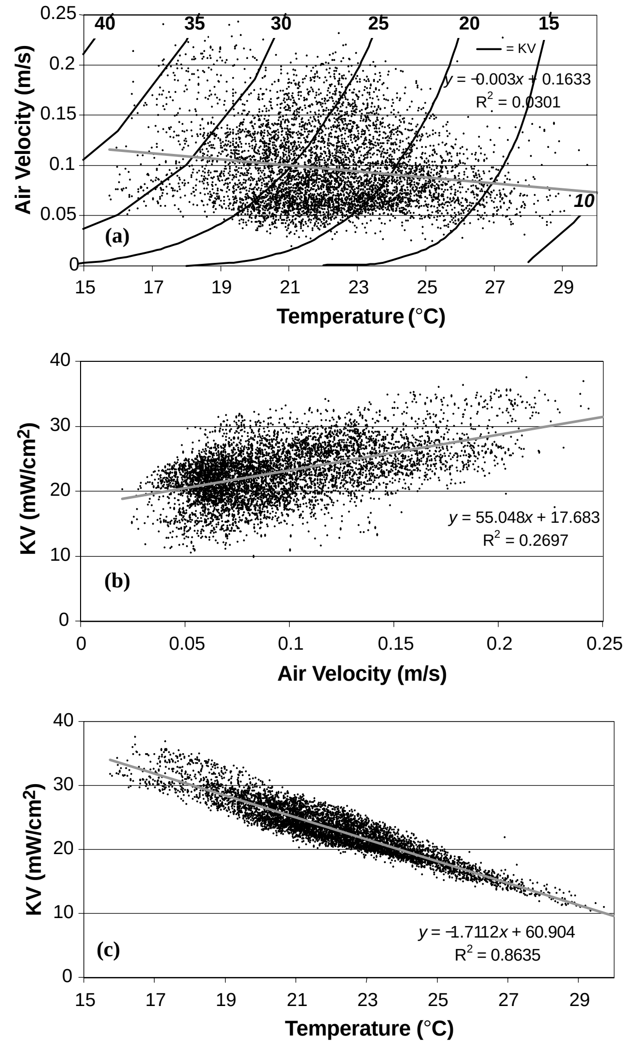

Figure 4. Relationship between hourly average temperatures, air velocities, and kata-values for pen 9 during the eight experimental batches (gray lines are trendlines).

KV for two pens during a summer and a winter batch. The dotted vertical lines indicate day 18, when the piglets were weighed.

Despite the change in climate computer settings of 10°C to 11°C during a batch (table 1), AOZ temperatures during a batch did not change by this same amount (fig. 5). This is partly due to the increased heat production of the piglets and partly to the limited possibilities to remove the heat from the room with ventilation air. During both batches in pen 3, temperature was higher and KV was lower than in pen 9. The frequent fluctuations in the curves show the day-night pattern of AOZ temperature and KV. In the beginning of the winter batch, the AOZ in pen 9 was "too cold." At the end of both batches, pen 3 became "too warm." During the winter batch, the temperature difference between pen 3 and pen 9 reached up to 7°C. This could result from the non-homogeneous air distribution due to an increased ventilation rate at the end of the batch.

Cumulative Excess of TNZ Limits

The cumulative excess of the TNZ limits in both °Ch and KVh for pens 3, 7, and 9 is shown in figure 6. Negative values indicate "too cold" conditions and are for days 0 to 18;

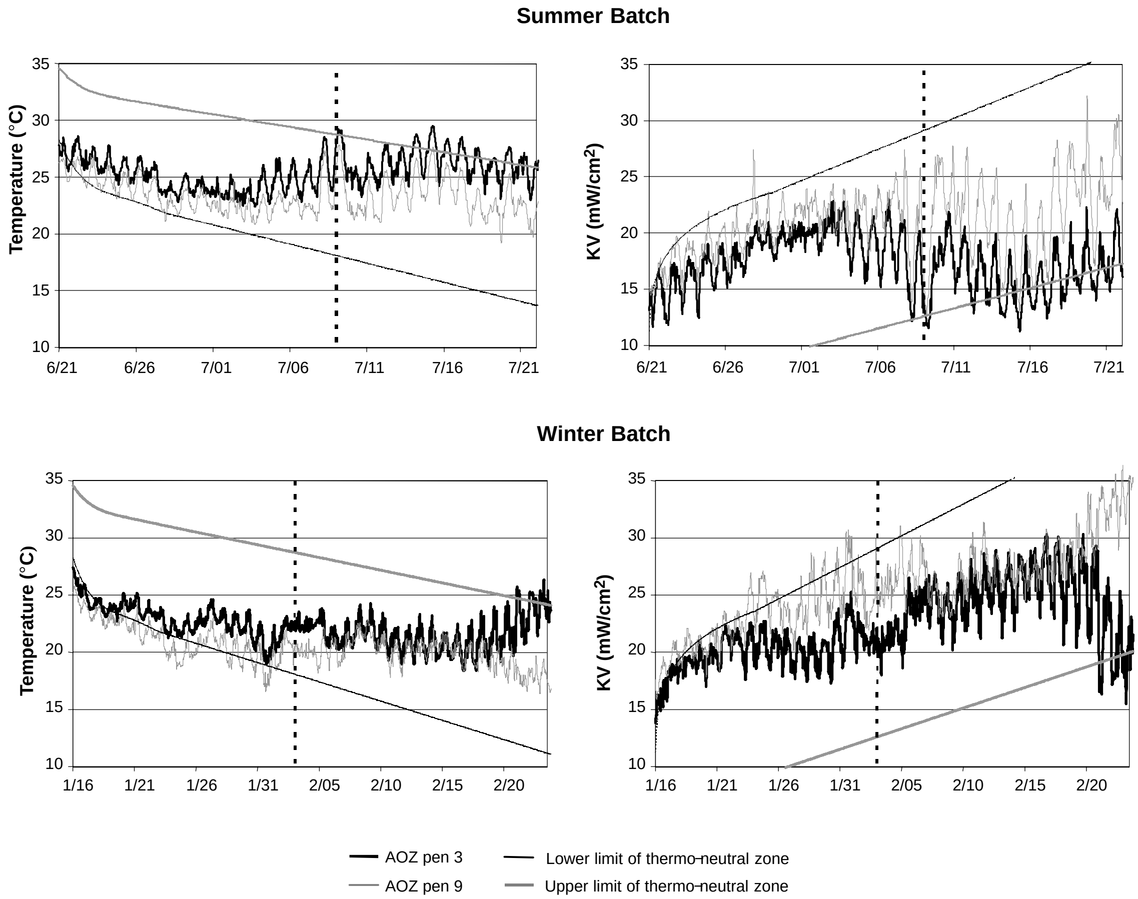

Figure 5. Course of hourly averages of the temperature and KV in pens 3 and 9 during a summer batch (batch 2) and a winter batch (batch 6) and the limits of the thermo-neutral zone.

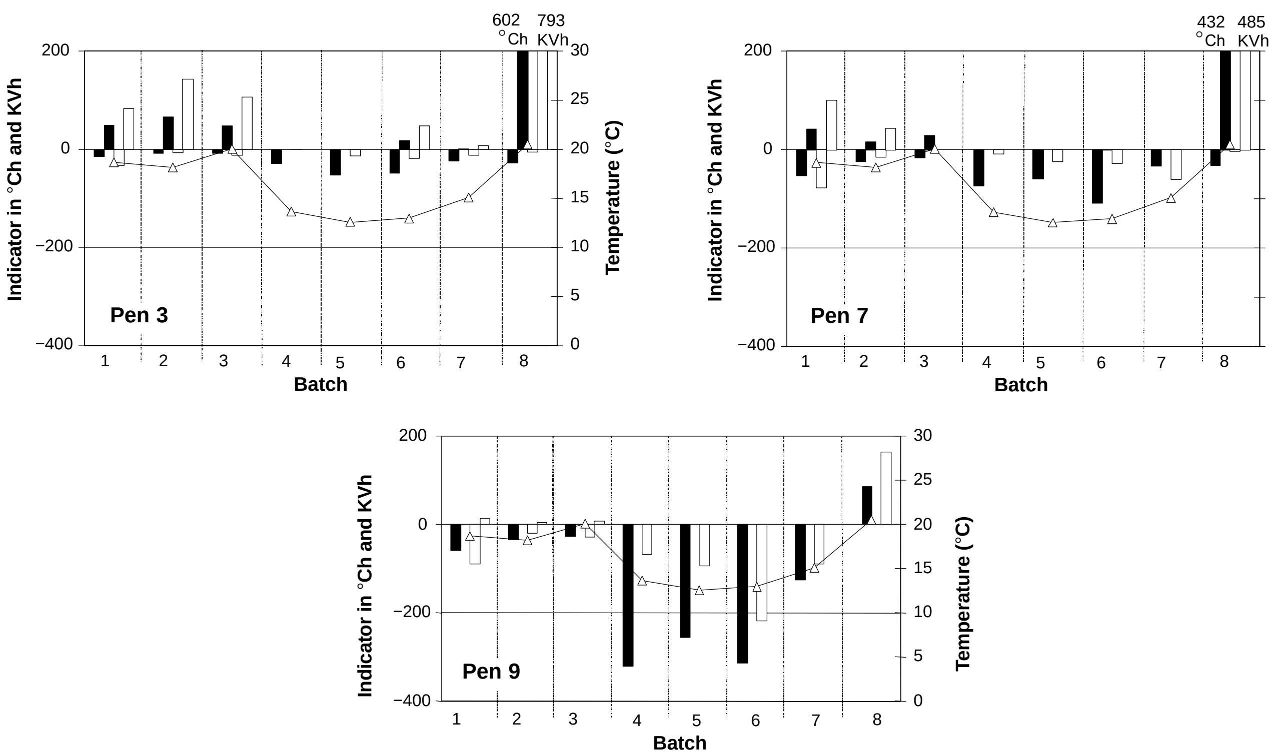

Figure 6. Cumulative excess of thermo-neutral zone limits (black bars = ˚Ch, white bars = KVh) in pens 3, 7, and 9 (negative values = "too cold" for days 0 to 18; positive values = "too warm" for day 18 to end of batch), and the average air temperature in the inlet (lines with triangles) during the eight experimental batches. ◦

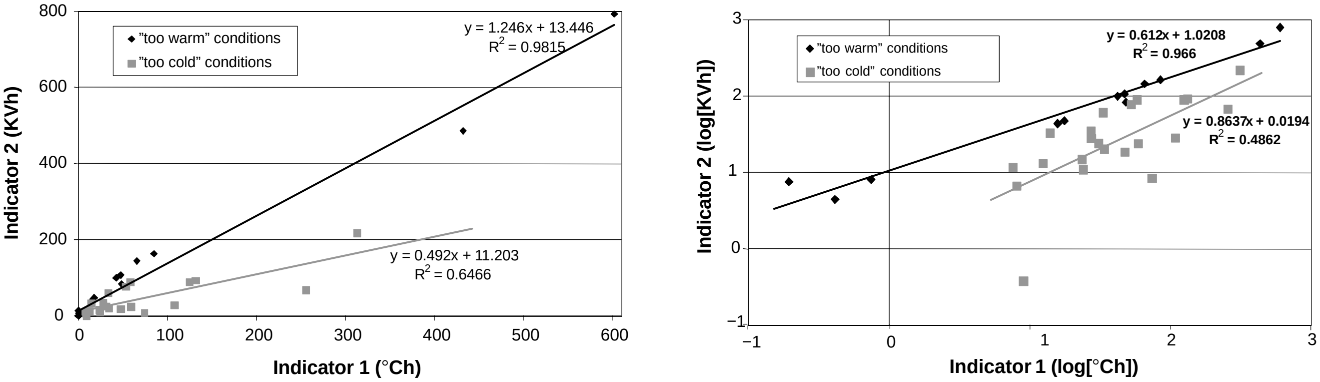

Figure 7. Relation between the cumulative excess of TNZ limits expressed in °Ch and KVh (on natural scale and logarithmic scale) in pens 3, 7, and 9 over the eight experimental batches.

positive values indicate "too warm" conditions and refer to day 18 to end of batch.

There were large differences in cumulative excess of the TNZ limits between pens and between batches. Batches in the winter period (batches 4, 5, and 6) were much colder than the other batches, and pen 9 was colder than pens 3 and 7. In batch 4, the highest cumulative excess "too cold" (319°Ch) was recorded in pen 9; in batch 6, the highest cumulative excess "too cold" (217 KVh) was also recorded in pen 9. Of the remaining batches, batch 8 was extremely warm; in pen 3, 602°Ch and 793 KVh were recorded.

To compare the values of both indicators per pen per batch, they were plotted against each other. This was done for the real value and the logarithm. The logarithmic plot was made to reduce the influence of some extreme high values of the indicators on the correlation (batch 8), excluding data points where one of the indicators (or both) had the value 0.

The result of the linear regression analysis showed that all relations were significant ($P < 0.001$). Figure 7 shows that the values of both indicators for "too warm" conditions are strongly correlated ($R^2 > 0.96$). For "too cold" conditions, the correlation is less ($R^2 > 0.48$). This confirms the observation in figure 4c, where KV varied more at relatively low temperatures.

Cumulative Excess Per Pen and Animal Performance

The pen average cumulative excess of temperature and KV outside the TNZ, after data selection according to the criteria given earlier in the Material and Methods section, is shown table 2. Data for day 18 to end of batch 8 were ignored because of the extremely warm AOZ conditions. After this selection, the maximum cumulative excess "too warm" was 65°Ch and 143 KVh (both recorded in pen 3 during batch 2).

Table 2 shows that pens 2 and 10 had on average the highest cumulative excess for indicating "too cold" conditions. Both pens were on the right side of the operator walkway in the room. Behind the non-insulated wall on this side of the room was the relatively cold central alley. The average cumulative excess for indicating "too warm" conditions was generally lower than for "too cold" conditions, and was highest in pen 3. Except for pens 1 and 2 in the front of the room that bordered the colder central alley with a non-insulated wall (fig. 3), the pens generally became colder towards the back of the room (from pens 3 to 9, or from pens 4 to 10).

Table 2 also shows pen average piglet performance after applying the selection criteria. These criteria resulted in ignoring seven batch average animal performance values because two or more piglets were culled in one pen during one batch, and six batch average values were ignored because the average piglet weight at the end of the batch was lower than 18 kg. There were clear and significant differences in growth for days 0 to 18, feed conversion ratio for days 0 to 18, and feed intake between pens. Pen 6 had the worst results for days 0 to 18, pens 4 and 7 the best. For day 18 to end, the differences between pens were less.

Table 2. Pen average cumulative excess of TNZ limits for temperature and KV, and pen average growth per piglet per day, feed conversion ratio, and daily feed intake per piglet separated for days 0 to 18 and for day 18 to end of the batch.[a]

Pen	Cumulative Excess "too cold" Day 0 - 18		Cumulative Excess "too warm" Day 18 - End		Growth per Piglet (kg/day)		Feed Conversion Ratio (kg / kg)		Feed Intake per Piglet (kg/day)	
	°Ch	KVh	°Ch	KVh	Day 0 - 18	Day 18 - End	Day 0 - 18	Day 18 - End	Day 0 - 18	Day 18 - End
1	106	−	7	−	0.235 a,b	0.536 a	1.69 a,b	1.74	0.392 a,b,c	0.930 a,b
2	178	−	8	−	0.236 a,b	0.522 a	1.78 b,c	1.71	0.420 b,c	0.892 a,b
3	19	16	26	65	0.233 a,b	0.514 a	1.70 a,b	1.74	0.386 a,b	0.885 a,b
4	50	−	15	−	0.252 b	0.571 a	1.61 a,b	1.75	0.406 b,c	0.998 b
5	40	−	12	−	0.252 b	0.514 a	1.73 a,b,c	1.78	0.430 c	0.911 a,b
6	100	−	10	−	0.206 a	0.530 a	1.90 c	1.73	0.399 b,c	0.912 a,b
7	55	37	14	50	0.230 a,b	0.510 a	1.60 a,b	1.72	0.356 a,b	0.812 a
8	118	−	7	−	0.230 a,b	0.521 a	1.72 a,b	1.78	0.387 a,b	0.906 a,b
9	133	92	0	5	0.245 a,b	0.526 a	1.64 a,b	1.78	0.399 b,c	0.933 a,b
10	179	−	4	−	0.249 b	0.517 a	1.65 a,b	1.81	0.408 b,c	0.942 a,b

[a] Values in the same column followed by different letters are significantly different ($P < 0.05$).

Table 3. Results of the statistical analysis of the data on animal performance.

	Explanatory Variable *X*											
	Cumulative Excess in °Ch						Cumulative Excess in KVh					
			X		Starting Weight[d]				*X*		Starting Weight[d]	
Dependent Variable Y	N[a]	% of Var.[b]	P	Factor[c]	P	Factor	N[a]	% of Var.[b]	P	Factor[c]	P	Factor
Day 0 - 18 ("too cold")												
Pen average												
Feed conversion	66	−−	0.865	−−	0.293	−−	18	−−	0.749	−−	0.843	−−
Daily growth	66	−−	0.520	−−	0.201	−−	18	−−	0.996	−−	0.365	−−
Daily feed intake	66	−−	0.167	−−	0.758	−−	18	−−	0.499	−−	0.589	−−
Individual												
Daily growth	611	−−	0.775	−−	0.681	−−	175	−−	0.798	−−	0.714	−−
Day 18 - end (too warm")												
Pen average												
Feed conversion	58	12.2	0.013	0.0024	0.069	0.028	11	−−	0.565	−−	0.813	−−
Daily growth	58	22.6	<0.001	−0.0022	0.024	0.010	11	−−	0.411	−−	0.367	−−
Daily feed intake	58	20.1	0.006	−0.0030	0.005	0.028	11	−−	0.438	−−	0.655	−−
Individual												
Daily growth	545	12.6	<0.001	−0.0023	<0.001	0.019	158	15.6	0.021	−0.0006	<0.001	0.027

[a] The number of observations (N) is different in some cases from the expected value based on the number of experimental batches and pens. Besides the mentioned selection criteria, reasons for this are: (1) during batch 8 in pens 9 and 10, the temperature was not measured on days 1 to 18, and (2) during batch 3, the air velocity was not measured in pen 7.

[b] "% of Var." = percent of variance accounted for.

[c] This factor indicates the effect of either an excess of 1°Ch or 1 KVh on the average animal performance variables for days 0 to 18 or for day 18 to end. By multiplying the factor with *X*, the estimated effect can be calculated.

[d] For days 0 to 18, this is the starting weight; for day 18 to the end, this is the weight on day 18.

In table 3, the results of the statistical analysis (eq. 2) of the data on animal performance are presented. "Too cold" periods did not significantly affect the animal performance. "Too warm" periods (expressed in ˚Ch) significantly affected the feed conversion, daily growth (both pen average and individual), and daily feed intake. For example, the factors indicate that 50˚Ch "too warm" in one pen after day 18 of one batch results in a higher feed conversion of 0.12 kg feed /kg growth (= 50˚Ch × 0.0024), a reduced daily growth of 0.11 kg/animal (= 50˚Ch × 0.0022), and a reduced daily feed intake of 0.15 kg/animal (50˚Ch × 0.0030) in this period. The percentage of variance accounted for by the analysis is a summary of how much of the variability of the data can be explained by a fitted regression model, and indicates that there were factors other than those used in the analysis that affected animal performance. The effect of the cumulative excess expressed in KVh for "too warm" conditions showed less significant results, probably due to the limited number of available data.

DISCUSSION

In this study, two evaluation methods were introduced that express the quality of the thermal environment in the AOZ of weaned piglets during a batch. The indicators were based on the cumulative excess of the TNZ limits by temperature expressed in ˚Ch or by kata-value (KV) expressed in KVh. Both indicators revealed good insight into the differences in AOZ climate between pens in a door-ventilated room. Colder pens in the back and next to non-insulated walls in the room and warmer pens in the middle could be distinguished. This confirms results of in earlier studies on the door-ventilation systems (Van Wagenberg and Smolders, 2003; Van Wagenberg and de Leeuw, 2003; Van Wagenberg et al., 2004) and confirms that focusing on AOZ climate control instead of room climate control in pig rooms is important.

There was a significant ($P < 0.001$) and strong ($R^2 > 0.96$) correlation between the two indicators for "too warm" conditions. Moments that where "too warm" regarding AOZ temperature were also "too warm" regarding KV in the AOZ. This can be explained. At locations in the AOZ with a large amount of fresh air, the temperature is expected to be relatively low and the air velocity relatively high. The air temperature distribution gives information on the fresh air distribution in a room with an internal heat load (Boonen et al., 2002). However, for "too cold" conditions, the indicators showed less correlation ($R^2 > 0.48$). This means that taking air velocity into account for recognition of "too cold" conditions can have surplus value. But even when air velocity is ignored in the change of focus from room climate to AOZ climate, important improvements in climate control systems can be achieved by reducing temperature differences between pens and by better control of AOZ temperature.

The TNZ limits in the evaluation method were based on the average animal performance in the room. This is disputable, because individual animals with other than average performance will have other TNZ limits. As a target, we chose thermal conditions in all pens that are optimal for piglets with average performance. Piglets also have mechanisms that influence TNZ limits, like adapting behavior or feed intake (Van Ouwerkerk, 2000; CIGR, 2002). However, for defining TNZ limits to be used in evaluating thermal environment, it is hard to take these individual adaptations into account.

A relationship between the indicators for "too warm" conditions and animal performance was found. The significant relationship found between the value of the indicators and the animal performance cannot simply be extrapolated to other batches in other situations. For example, for the 602˚Ch "too warm" condition during batch 8 in this study, the effect per °Ch excess of TNZ limits will be different from the factors presented in table 3.

No relationship with animal performance was found for "too cold" conditions, while the values of the indicators for "too cold" conditions were higher than for "too warm" conditions. Assuming that the TNZ limits used are currently valid for piglets, this finding is surprising. Constant "too cold" conditions are known to reduce feed conversion ratio (with about $0.044\,^{\circ}C^{-1}$), cause an increase in feed intake, and/or result in a reduced growth rate (Le Dividich et al., 1992). A first explanation of the different outcome can be that the reported data are based on constant "too cold" conditions, while in our study "too cold" conditions mainly occurred during night periods, while conditions were warmer during the day. Second, there was a possible difference between the values measured in the AOZ and the thermal conditions experienced by the piglets. In the experiment, AOZ temperature was measured on the side of the pen opposite the feeder. Young piglets under cold conditions will prefer to lay behind the feeder, where the local microclimate is warmer (Van Wagenberg et al., 2005). Third, in the data analysis, some data for culled and slow-growing animals were neglected, and these animals could have been exposed to "too cold" conditions. In addition, the batch effect was ignored in the data analysis, assuming that this normally reveals an AOZ climate effect, while other factors will also play a role, such as animal health and the genetic features of the animals in a certain batch. Fourth, the evaluation methods neglected some aspects of the interaction between thermal environment and piglets, including: (1) fluctuations of the thermal environment (outside and within the AOZ), although it is known that quick changes in thermal environment under cold conditions are harmful (Scheepens et al., 1991); (2) pigs' ability to adapt to conditions of constant climatic stress (Verhagen et al., 1987; Le Dividich and Herpin, 1994); and (3) diurnal variation in the heat production of piglets and thus in TNZ limits (Pedersen and Rom, 1998).

For a more detailed study of the response of piglets to a certain course of the climatic environment, comparative research in climate chambers could be done. Certain temperature or KV courses (based on encountered situations in the AOZ of practical buildings) could be used, and animal performance data may be compared. This will help to quantify the importance of staying within the TNZ and to determine the costs of exceeding this zone due to less efficient production. This information could be used to evaluate and optimize climate systems in pig houses, with the technical performance on the one hand and costs on the other.

CONCLUSION

Two numerical indicators were introduced that reveal how much the air temperature and kata-value, which combines air velocity and air temperature, in the animal-occupied zone (AOZ) in a pen exceed the thermo-neutral zone (TNZ) of a batch of weaned piglets:

- Both indicators allow sensitive discrimination in thermal conditions in a pig room both in space and time, i.e., between the pens and between batches.
- In a door-ventilated room, the value of the indicators varied largely between pens and batches, thereby clearly distinguishing colder pens in the back of the room and next to non-insulated walls from warmer pens in the middle.
- For recognition of "too cold" conditions in the AOZ, both air temperature and air velocity should be measured. For "too warm" conditions, air temperature alone predicts the kata-value sufficiently.
- The cumulative excess in air temperature above the TNZ, indicating "too warm" conditions, significantly deteriorated animal performance.

This study revealed that focusing on the AOZ is necessary for creating an optimal climate for weaned piglets. The methods presented can be used as a tool in the technical evaluation and comparison of climate system designs.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the funding provided for this project by the Dutch Ministry of Agriculture, Nature and Food Quality.

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