An Ammonia-Controlled Ventilation System for Fattening Pigs

Walter Grotz, Barbara Rathmer, Andreas Gronauer and **Hans Schön**
Bayerische Landesanstalt für Landtechnik Weihenstephan, Freising-Weihenstephan

In farm animal housing, a good stall climate is the prerequisite for animals and humans in the stall to stay healthy. Taking this into account, the legislator has set maximum limits for certain gaseous pollutants such as ammonia (NH_3) in the calf- and pig husbandry decrees. At the Bavarian Research Center for Agricultural Engineering, an ammonia-controlled ventilation system with NH_3 as an additional regulation variable besides the temperature was developed in cooperation with ventilation companies and successfully tested in a stall for fattening pigs. Low-cost NH_3 sensors, which were tested during the project at a gas dilution station in the laboratory and in practical trials in the stall, currently do not yet seem suitable for long-term, reliable use in an ammonia-controlled ventilation system.

Keywords
Ammonia, controlling, ventilation, sensors

Introduction and Description of the Problem

Even if high concentrations of gaseous pollutants in the stall do not necessarily lead to performance losses, reasons of animal friendliness and –health require the best possible stall climate. Not least, humans working in the stall are interested in the lowest possible pollutant concentrations, which, however, are particularly high at low ventilation rates, i.e. in the transitional periods and in the winter months. Legal regulations [1], [2] determine the maximum values of the concentrations of the gaseous pollutants carbon dioxide (CO_2), hydrogen sulphide (H_2S) and ammonia (NH_3), which are not supposed to be exceeded in the animal area. The DIN 18910 standard [3] provides orientation with regard to the dimensioning of ventilation systems in closed stalls. This standard determines minimum air rates for winter- and summer operation depending on the animal species and animal weight. The calculations are based on the water- and carbon dioxide balance. Due to the complex formation processes of air pollutants, which originate especially from the decomposition of excrement, the dimensioning of the ventilation system according to DIN 18910 cannot guarantee that the limits set in references [1] and [2] are kept for all gases. For this reason, it is necessary to develop a ventilation control system which includes the concentration of at least one of these pollutants as a control variable. At the Bavarian Research Center for Agricultural Engineering of the Technical University of Munich, such a control system was developed in co-operation with the companies Ziehl-Abegg and Schönhammer Lüftungstechnik. In addition to the temperature, ammonia (NH_3) was integrated as an additional control variable. NH_3 was chosen because relatively low concentrations of this gas can already lead to harmful effects. Therefore, it is more suitable for the qualitative evaluation of the stall climate than CO_2, which causes no immediate harmful effect even if the concentration is several times higher than the limit of 3,000 ppm.

Design of an Ammonia-Controlled Ventilation System

The basic design of an ammonia-controlled ventilation system has already been described in Landtechnik [4]. An ammonia-controlled ventilation system consists of a process controller which compares the command variables of the control variables temperature and NH_3 with the current values measured by the specific sensors. This serves as the basis for the calculation of the manipulated variables for the actuators ventilator and heating system.

Sensors

The NH_3 sensors used must be inexpensive, though reliable. In the stall, where robust systems are required, no suitable sensors are available at present for the continuous measurement and monitoring of gaseous pollutants because the available systems have been designed for industrial applications. For this reason, this research project included tests of different low-cost sensors for ammonia-controlled ventilation [4]. These sensors shown in an overview in Table 1 were tested in the laboratory and in practice. The practical tests were divided into phases of continuous and intermittent operation. The quality of a measuring technique can be determined according to the VDI guideline 2449 [5]. An important criterion for these measurements is selectivity, which describes “the dependence of the measurement value on the presence of other air quality characteristics besides the one being sought”, i.e. cross-sensitivity. Cross-sensitivity can only be measured in the laboratory because in practical trials other substances, which cannot be added in defined concentrations in the laboratory, are present as well.

Demands on the Sensors

For use in an ammonia-controlled ventilation system, the highest permissible measuring inaccuracy is 5 ppm at NH_3 concentrations of up to 30 ppm. At higher concentrations, measuring inaccuracy should not exceed about 20% of the displayed value. In addition to low investment cost, the NH_3 sensors should be stable over long periods in order to keep maintenance expenses low and to guarantee optimal operating safety.

Material and Methods

Control Process

Since NH_3 is integrated into the control process as a second control variable beside the temperature, the previous control process must be adapted. If the temperature of the fresh air is far below the set temperature in the stall, NH_3 concentration cannot be reduced at will because in this case the set temperature could not be kept. If nevertheless lower NH_3 concentrations than in a temperature-controlled reference stall are to be reached, an infinitely variable heating system is necessary. NH_3 concentration as input variable and the heat output of the heating system as output variable were integrated into the control software. The left side of **Figure 1** shows how the manipulated variable fan rev is composed in the NH_3 controlled ventilation system. If the set temperature is exceeded, NH_3 is weighted less because in this case heat conveyance has priority. If the temperature falls below the set value, NH_3 is also continuously weighted less until the maximum heat output of the heating system is reached. The right side of the figure shows how the manipulated variables heating voltage and fan rev are continuously increased up to the maximum (10 V and 100%) at the upper and lower end of the control range if the temperature exceeds or falls below the set value.

Sensors and Measuring Instruments

The first part of the project focused on the selection of suitable ammonia sensors. First, sensors were chosen for thorough examinations according to the criteria price and functional principle. The investment cost in combination with service life are the most important obstacles in practical use in agriculture. Selection according to the functional principle is necessary because electro-chemical sensors, for example, are offered by many companies. In most cases, however, their only distinctive feature is the evaluation electronics.

In the laboratory, the sensors are calibrated as far as necessary and possible. Some sensors are delivered uncalibrated. Others cannot be calibrated for technical reasons and are therefore operated with a fixed company setting. Measuring inaccuracy and cross-sensitivity to other gases can be determined at the gas generation and –mixing system GEMS2000. In practical tests, zero shift and the deviations of the sensor measurement values from the concentrations of the reference measuring instruments were established under the special conditions of the stall atmosphere. Those tested sensors and measuring instruments which are not included in the description given in reference [4] will be described briefly below.

Reference Measuring Instruments

In continuous operation, a photo-acoustic infrared spectrometer (PAS-IR) was used as a reference measuring instrument because this instrument proved itself worthy in laboratory tests and practical measurements and because both the measuring principle and the electronics are reliable [6].

In intermittent operation, a Fourier transform infrared spectrometer (FTIR-S) served as a reference instrument [7] because multi-gas analysis was necessary in another part of the project. During this period, the PAS-IR was used as an NH_3 sensor in NH_3-controlled ventilation.

PAS-MGU

Like the reference measuring instrument PAS-IR I, this is an ammonia measuring instrument which operates according to the PAS-IR principle. In contrast to the reference measuring instrument, a gas multiplexer is integrated into this instrument, which takes in sample gas from four different measuring points and, depending on the valve position, either admits it into the measuring chamber or disposes of it via a bypass. This instrument was tested because it allows to take samples from several compartments.

Opto-Chemical Sensor I (OC I)

The opto-chemical principle is based on the absorption of light by a layer sensitive to ammonia, which changes its colour if ammonia concentration alters. A light-emitting diode (LED) sends a light beam through the sensor substrate (S), which is refracted to a different degree depending on the ammonia concentration. After it has passed through the substrate, the light beam is collected by a photo transistor and compared with an unrefracted reference beam in the microcontroller. This functional principle is shown in **figure 2**.

Opto-Chemical Sensor II (OC II)

This sensor works like the opto-chemical sensor I (OC I). A light beam is conducted through a planar waveguide (in this case a glass plate) which it enters within the critical angle of incidence. Thus, the beam is totally reflected. At the surface, the duct is coated with an NH_3-sensitive layer which reacts to a change in NH_3 concentration by altering its colour. At those points where the light beam is reflected, an evanescent wave leaves the waveguide. Depending on the coloration of the surface, the intenisty of this wave varies and therefore is a measure of NH_3 concentration.

Table 1 provides an overview of the tested sensors with their functional principles and the investment costs.

Testing Mode and Experimental Set-Up

The sensors and measuring instruments are tested in the laboratory at the gas generation and –mixing unit GEMS2000, which produces single gases and gas composites in variable concentrations. Additionally, it is possible to add defined concentrations of moisture through a capillary system. This is important because many measuring systems have a high cross-sensitivity to water vapour and because stall air generally has high, fluctuating H_2O concentrations. Under controlled conditions, the sensors are calibrated, cross-sensitivities to other gases such as methane and water are defined, and mea-

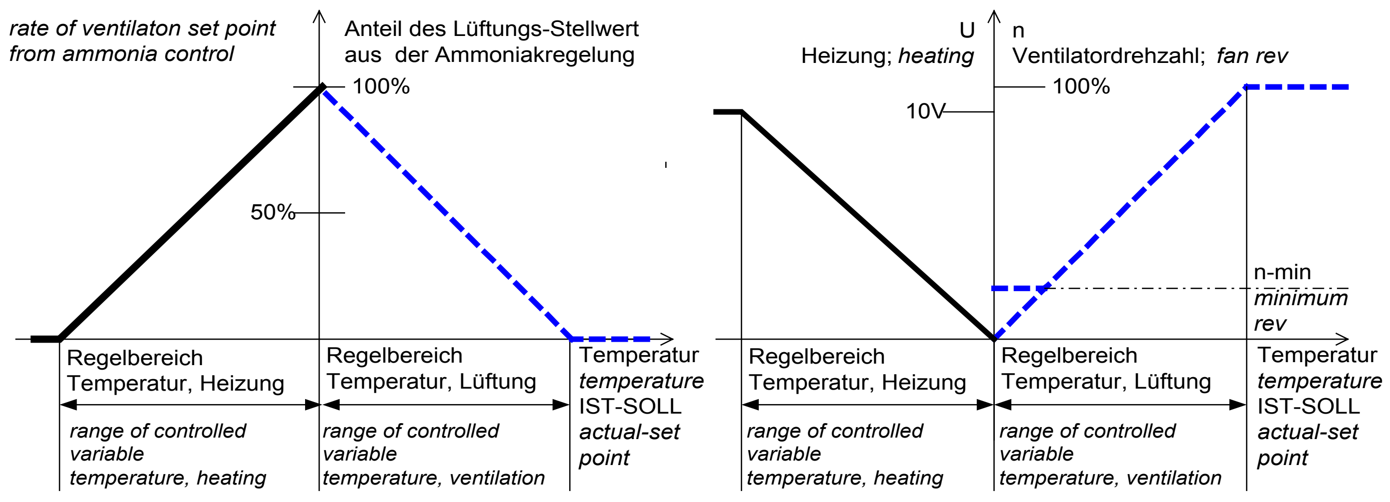

Figure 1: Control process in ammonia-controlled ventilation (source: Ziehl-Abegg)

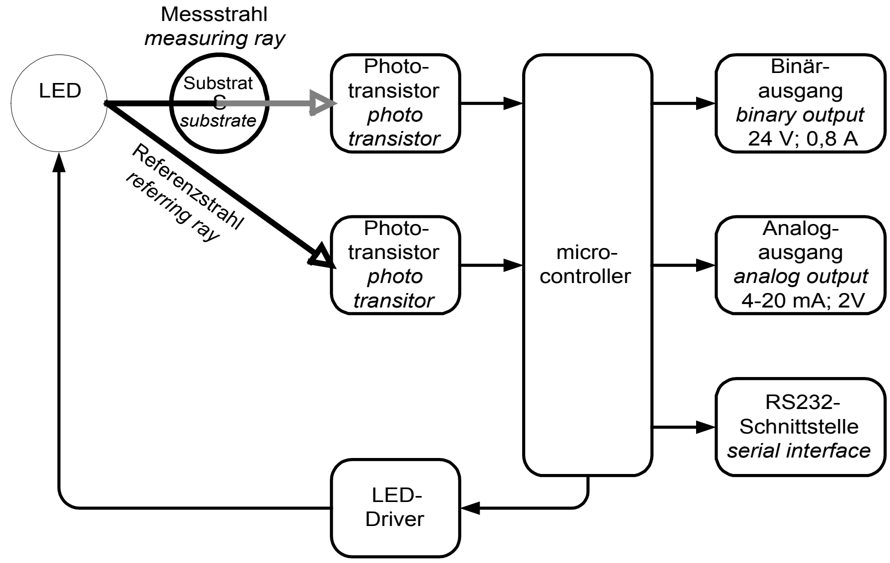

Figure 2: Design of the opto-chemical sensor I (OC I) (according to iRAS GmbH)

Table 1: Overview of the tested ammonia sensors

Sensor	Functional principle	Cost (approx.)	Mode of operation
Reference	PAS-IR	14,000,-	In the measuring cell, infrared light of a certain wavelength encounters gas which is warmed up through absorption and expands. Pressure change is registered by a measuring microphone.
PAS (MGU)	PAS-IR	10,000,-	
MOS I	Alteration of resistance on a semiconductor surface	500,-	The measuring gas collects on the semi-conductor surface and thus changes the conductibility of the latter.
MOS II		1,000,-	
OC I	Opto-chemical	1,000,-	A light beam penetrates a substance which reacts with the measuring gas and changes its optical characteristics. The alteration of the light signal is measured.
OC II	Opto-chemical	1,800,-	
ECS I	Electro-chemical	3,500,-	The gas to be measured reacts with an electrolyte or an electrode, which changes electric potential.
ECS II	Electro-chemical	3,000,-	

suring inaccuracy is determined. The sensors to be examined are connected to the gas exit of the GEMS2000 and, depending on their design, the test gas (-composite) is admitted either actively or passively.

In practice, tests were carried out in continuous operation (continual eight week measurement in the fall, phase I) and in intermittent operation in two test phases (two weeks in the winter (phase IIa) and four weeks in the spring (phase IIb)) with stall air from pig houses. In continuous operation, stall air is admitted without interruption. In intermittent operation, fresh air (20 minutes) and stall air (20 minutes) are alternately pumped into the sensor chamber via a gas multiplexer (cf. **figure 3**). For practical examination, the sensors are mounted to a sensor chamber. The reference measuring instrument is installed between the sensor chamber and the pump. This instrument either actively sucks the measuring gas in the bypass out of the measuring gas duct, or the gas flows through the passive instrument (like in the case of the FTIR spectrometer). The ammonia concentrations measured by the sensors and the reference measuring instrument are continuously recorded by a data logger and evaluated. Figure 3 shows the described experimental set-up.

Results

Process Control

In general, the control system shown in Figure 1 proved functional. However, it turned out that NH_3-controlled ventilation cannot be operated without a minimum ventilation rate either because, at low outside temperatures, the control system can cause relatively large fluctuations of the stall temperature. If the set temperature is kept and if NH_3 concentration exceeds the set NH_3 value, NH_3 is weighted fully by the control system, and the regulation variable of the ventilation system increases. This leads to large quantities of cold air being admitted very quickly, and the temperature falls into the lower control range. As a consequence, the ventilation rate sinks towards zero, and the heat output is set to its maximum value. Thus, the set temperature is reached again within a short time. However, NH_3 is also fully weighted for control again, and the above-described process repeats itself. These cyclical control circuits lead to a draft and to a very uneven stall climate, which is undesirable, especially in pig housing. If a minimum ventilation rate is activated as a manipulated variable, the large ventilation fluctuations at low outside temperatures are suppressed. For safety, an automatically increasing minimum air rate (from 0 to 20%) at falling outside temperatures was integrated into the control process.

Laboratory

Linearity

First, NH_3 concentrations of 10, 20, 35, and 50 ppm as well as synthetic air were admitted to the sensors at the gas mixing station in order to examine linearity. In a second step, 12,000 ppm of H_2O were added. The results are shown in **table 2** as a

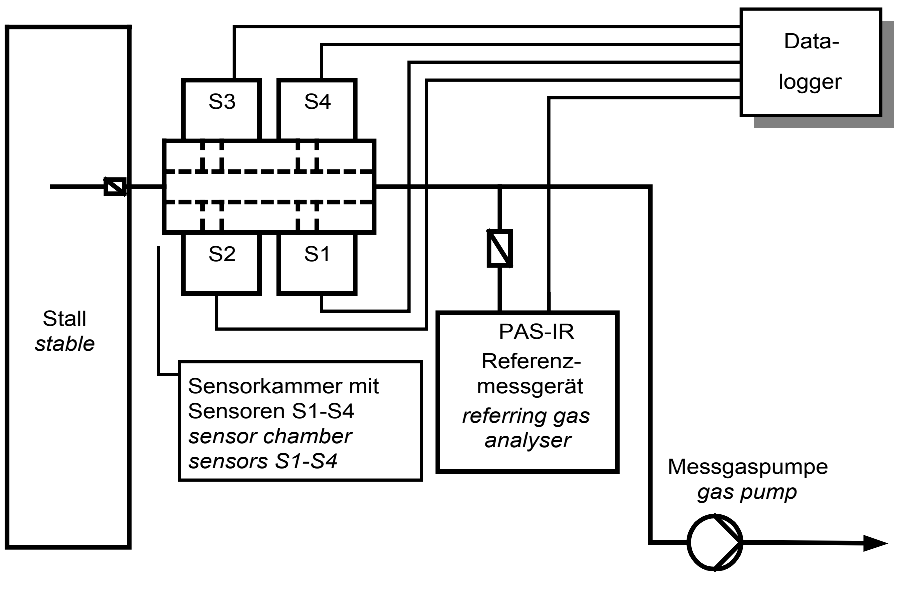

Figure 3: Diagram of the experimental set-up for practical sensor testing

function of the output voltage. The results show that H_2O concentration can have an influence on the function of the sensor. Some of the non-linear functions can be attributed to the fact that the sensors, which are designed for larger measuring ranges, were not calibrated according to the instructions of use. Instead, only the sensitivity of the sensors was increased. Linearity does not exert any influence on the use of these sensors in an ammonia-controlled ventilation system (provided it is constant) because a function or a table containing concentrations and corresponding output voltages can be integrated into the control software if the connections between NH_3 concentration and output voltage are known.

Table 2: Calibration functions of the sensors

Sensor/ Instrument	Calibration function (0, 10, 20, 35, 50 ppm NH_3)	Stability index R^2	Calibration function (12.000 ppm H_2O und 0, 10, 20, 35, 50 ppm NH_3)	Stability index R^2
PAS-MGU	$y = 105.66x + 0.0065$	0.9996	$y = 99.689x + 0.4866$	0.9993
OC II	$y = 281.29x^3 - 305.66x^2 + 133.47x - 18.495$	0.9994	$y = 125.88x^3 - 14.828x^2 - 17.945x + 3.4539$	0.9503
ECS II	$y = 495.28x - 98.99$	0.9989	$y = 518.65x - 106.81$	0.9945
OC I	$y = 312.7x - 62.957$	0.9982	$y = 239.61x - 49.603$	0.983
ECS I	$y = 137.54x - 26.849$	0.9996	$y = 132.75x - 25.371$	0.9995
MOS I	$y = 409.07x - 81.65$	0.9984	$y = 0.337e^{5.1831x}$	0.9966
MOS II	$y = 1889.8x^3 - 1052.4x^2 + 238.84x - 21.095$	0.9895	$y = 2258.5x^2 - 911.9x + 91.856$	0.9995

Table 3: Sensor testing, laboratory evaluation: cross-sensitivity to water, inaccuracy at variable gas composites

		PAS-MGU	MOS I	MOS II	OC I	OC II	ECS I	ECS II
Cross-sensitivity to water [ppm/%H_2O]		-2.8	0.1	1.1	-1.9	0.1	1.2	-1.7
20 ppm NH_3 + 6000 ppm H_2O	Measuring inaccuracy [ppm]	-2.6	-2.3	-3.4	**5.2**	**1.7**	0.8	-0.9
20 ppm NH_3+ 12000 ppm H_2O		-4.0	-5.0	**-23.8**	**12.0**	**16.7**	1.4	-2.9
20 ppm NH_3+ 18000 ppm H_2O		-2.4	-3.2	**-7.7**	**6.9**	**11.6**	1.3	-0.2
30 ppm NH_3 + 12000 ppm H_2O		-1.7	-2.5	-2.9	**5.7**	**15.7**	1.7	0.2
50 ppm NH_3 + 12000 ppm H_2O		-	-5.0	-9.3	**10.6**	**15.0**	1.1	-0.9
20 ppm NH_3+ 12000 ppm H_2O +20 ppm CH_4,+2 ppm N_2O +1000 ppm CO_2		-3.4	-3.7	**-8.4**	**13.0**	**7.2**	0.8	-0.1

Selectivity (Cross-Sensitivity) and Measuring Inaccuracy

Table 3 shows the results regarding selectivity together with the results concerning measuring inaccuracy. Cross-sensitivity to water was tested at different H_2O concentrations. Since, however, it cannot be excluded that the sensors also react to gases which have not been mentioned, selectivity tests were carried out with 1,000 ppm of CO_2, 20 ppm of CH_4, and 2 ppm of N_2O as single gases in these stall-typical concentrations. These tests did not indicate any cross-sensitivities. For this reason, the above-mentioned gases as a gas composite were additionally enriched with 20 ppm of NH_3 and 12,000 ppm of H_2O in order to be able to determine a cumulative effect of the gases on the measuring accuracy of the NH_3 sensors.

The water cross-sensitivity of all sensors was small because those calibration functions were employed which resulted from calibration with moist test gas (table 2). In the case of the PAS-MGU, it can be explained as the result of a zero drift which occurred shortly after calibration. The measuring accuracy of the sensors OC I, OC II, and MOS II were unsatisfactory (table 3, bold).

Practice

Continuous Operation, Phase 1

Continuous operation tests were carried out during an eight week test period. The concentrations in the test stall were relatively low (1 to 20 ppm). For the evaluation of the measuring inaccuracy of the sensors, the gas concentrations were divided into four classes comprising 5 ppm each. The mean values of each class were determined, and the measuring inaccuracy in comparison with the PAS-IR reference measuring instrument was calculated. This measuring inaccuracy was calculated in the first and last measuring week in order to register effects caused by the permanent admission of pollutant gases. This includes the ageing and "oversaturation" of sensors. **Figure 4** (sensors with larger deviations from the reference value) and **figure 5** (sensors with smaller deviations from the reference value) show the results of the sensor test in continuous operation. The first column represents the measurement value of the first week, the second column the value of the last week, during which no NH_3 concentrations > 15 ppm occurred. Constant deviations in all concentration classes indicate an offset. MOS II and OC I exhibit very large deviations from the reference values (figure 4) along with large standard deviations of the mean values. Hence, these sensors are not suitable for use in ammonia-controlled ventilation. In the case of ECS II, relatively large deviations of more than 10 ppm were observed which, however, are constant in all concentration classes and thus indicate a tolerable offset. Especially PAS-MGU, but also ECS I and MOS I meet most requirements for sensors (see above), especially at higher concentration levels. ECS I, however, changes its deviation from positive (1st week) to negative (last week). This indicates sensor oversaturation, which is well known in electro-chemical sensors. With increasing duration of measurement, OC II indicates lower concentrations. After the continuous measurement, this sensor was replaced with an instrument which, according to the manufacturer, had been developed further.

Intermittent Operation, Phases II a and II b

In intermittent operation (phases II a and II b), a gas multiplexer admits "pure" outside air to the sensors in 20 minute intervals for 20 minutes each. This rinsing with zero air is supposed to avoid oversaturation effects. **Figure 6** shows that the zero point of some sensors already shifts significantly several hours after the beginning of a measurement because they cannot regenerate completely after the admission of stall air and thus do not reach their zero point. The average NH_3 concentration level of the fresh air amounts to approximately 0.5 ppm (reference FTIR-S). During the measurements, this effect was always observed after measurement interruptions which lasted several hours and during which the sensors were rinsed with zero air. The increase and the reduction of the zero point level shown in Figure 6 is caused by the different NH_3 concentrations of the outgoing air from the stalls. The lower the NH_3 level was before rinsing with fresh air, the lower the zero point level generally is.

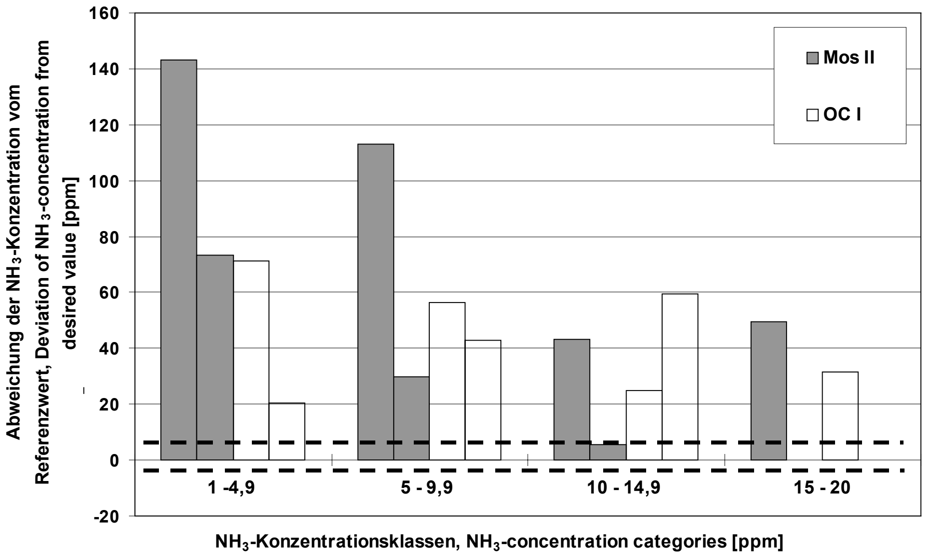

Figure 4: Results of sensor tests in continuous operation (phase I) and sensors showing large deviations from the reference value. The broken line indicates tolerable inaccuracy.

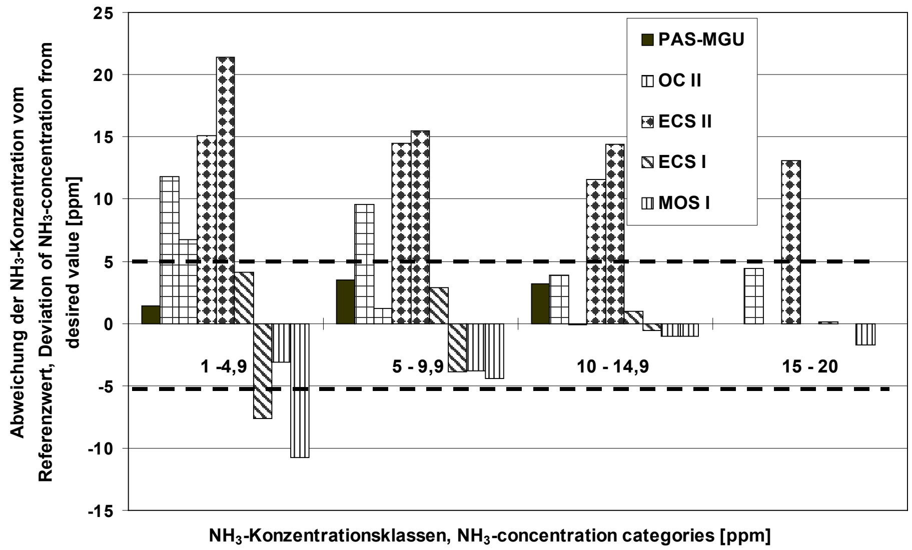

Figure 5: Results of sensor tests in continuous operation (phase I) and sensors showing minor deviations from the reference value. The broken line indicates tolerable inaccuracy. PAS-MGU was inoperative in the first week of testing.

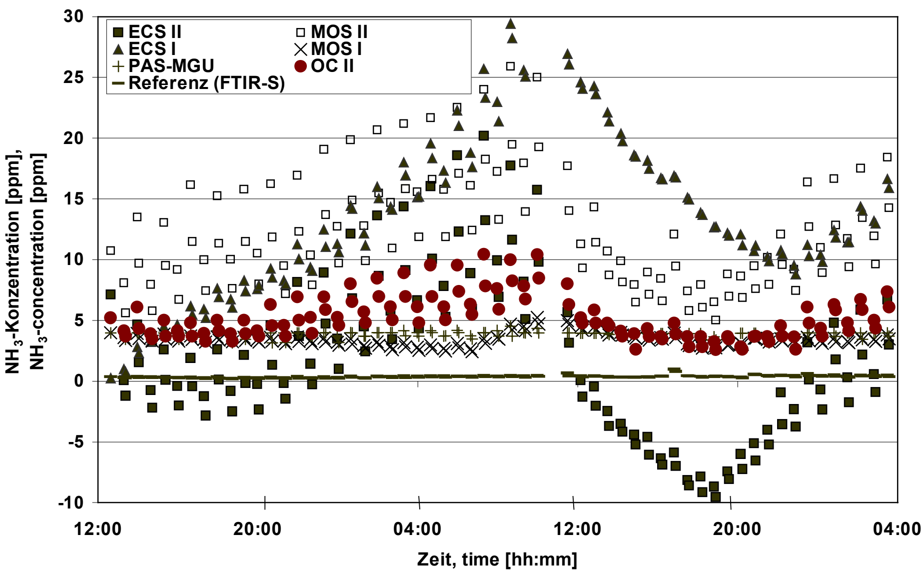

Figure 6: Sensor behaviour in intermittent operation with admission of outside air (phase II a)

Figure 7 (sensors with smaller deviations) and **figure 8** (sensors with larger deviations) show the deviations from the reference measuring instrument in intermittent operation. The first column represents the mean deviation from the average measurement value of the reference measuring instrument under winter conditions (phase II a; no values in the concentration classes 5-9.9 ppm, 10-14.9 ppm, and 15-19.9 ppm), the second column the deviations under spring conditions (phase II b). The average measurement value deviation of the PAS-MGU, which was only used in the spring, always corresponds to the permissible measuring inaccuracy. In the winter period, the OC II sensor positively deviates from the measurement value of the reference instrument. In spring, deviation is negative. At higher measurement values, MOS I significantly deviates from the reference value. In spring, deviation is slightly smaller. In contrast to this, the MOS II sensor by far exceeds the permissible measuring inaccuracy. ECS I and II do not meet the requirements either. During this test phase, the OC I sensor did not yield any utilizable results and could also no longer be calibrated.

Evaluation of the Sensor Tests

According to current knowledge, none of the tested low-cost sensors is suitable for permanent application in an ammonia-controlled ventilation system. In the laboratory tests, OC I, OC II (which was exchanged later), and MOS II did not meet the selection criteria. In practical operation, MOS II and OC I did not stay within the limits of the permissible measuring inaccuracy either. At low or high concentrations, the electro-chemical sensors ECS I and ECS II deviate far from the reference value, or they show non-uniform deviations from the reference value over longer periods and thus do not provide the user with reliable values. The OC II sensor has been improved in the second version. However, its values fluctuate heavily over time. Especially at high NH_3 concentrations, MOS I shows large deviations from the reference value. At least during the test phases, the tested PAS-MGU did not prove to be very reliable because it had to be repaired quite often. Otherwise, it would be an alternative to the low-cost sensors.

Conclusions

A pollutant-controlled ventilation system has been technically realized. Inexpensive sensor technology still needs to be optimized for this purpose. In current studies, this system is being evaluated under eco-

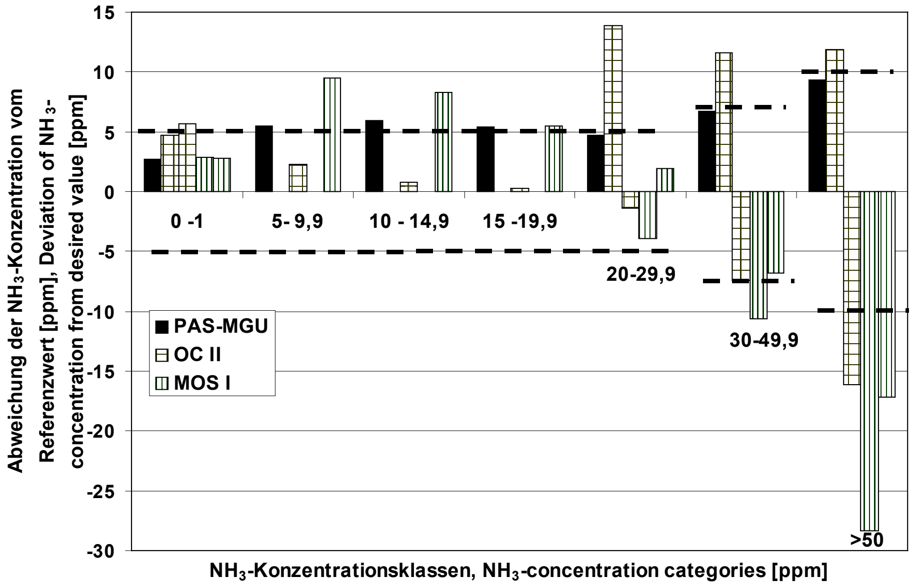

Figure 7: Results of sensor tests in intermittent operation (phase II a and phase II b) and sensors showing minor deviations from the reference value. The broken line indicates tolerable inaccuracy. PAS-MGU was inoperative in phase II a.

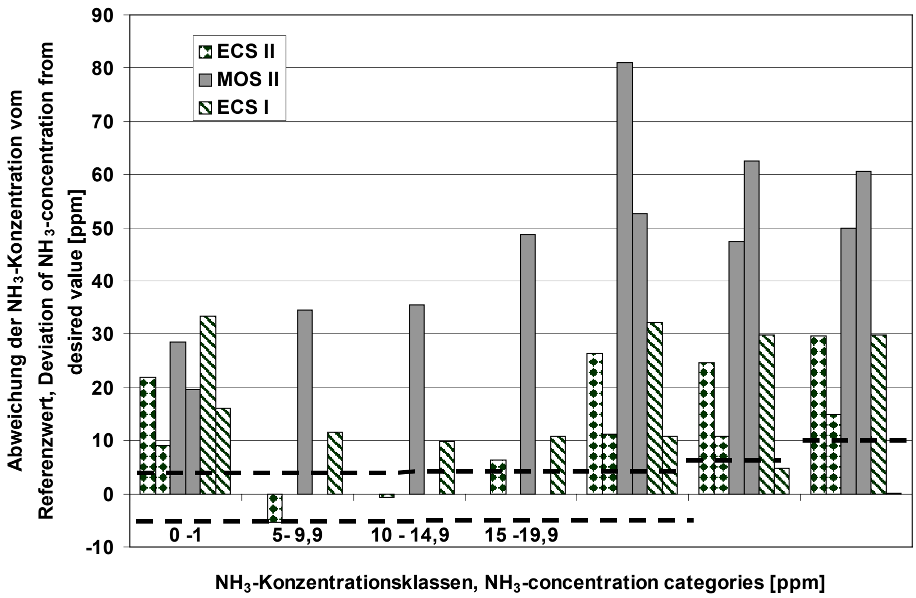

Figure 8: Results of sensor tests in intermittent operation (phase II a and phase II b) and sensors showing larger deviations from the reference value. The broken line indicates tolerable inaccuracy.

nomic and environmental-technological aspects, as well as according to criteria of animal friendliness.

References

[1] *BGBl* (Bundesgesetzblatt) (1992): Jahrgang 1992 Teil I, S. 1977-1980: Verordnung zum Schutz von Kälbern bei Stallhaltung (Kälberhaltungsverordnung).

[2] *BGBl* (Bundesgesetzblatt) (1994): Bekanntmachung der Neufassung der Schweinehaltungsverordnung, Bonn.

[3] *DIN,* Deutsches Institut für Normung e.V.(1992): Wärmeschutz geschlossener Ställe, Wärmedämmung und Lüftung, Planungs- und Berechnungsgrundlagen.

[4] *Grotz, W. und Gronauer, A.* (1998): Schadgassensoren. In: Landtechnik 53/6, 380-381.

[5] *VDI-Kommission Reinhaltung der Luft, Arbeitsgruppe zur Kennzeichnung vollständiger Meßverfahren* (1987): Grundlagen zur Kennzeichnung vollständiger Meßverfahren Begriffsbestimmungen. In: VDI-Handbuch Reinhaltung der Luft VDI 2449, Blatt 2, 2-6.

[6] *Neser, S., Gronauer, A. und Schön, H.* (1999): Vergleich der Emissivität von Mastschweinehaltungen mit Oberflur- und Unterflurabsaugung. In: Tagung: Bau, Technik und Umwelt 1999 in der landwirtschaftlichen Nutztierhaltung. Landtechnik Weihenstephan, Freising, 51-56.

[7] *Depta, G., Neser, S., Becher, S., Stanzel, H. und Gronauer, A.* (1996): Multigasanalyse der Emissionsraten landwirtschaftlicher Quellen, Darstellung der Meßverfahren FTIR und Laser-Anemometrie. In: Landtechnik 51, no.4, 206-207.

This research project is being financed by the Bavarian State Ministry of Food, Agriculture, and Forestry (promotion number: A/97/30). The authors would also like to thank Ziehl-Abegg GmbH, Schönhammer Lüftungstechnik, and Westfalen-Gas for their support.

Authors

Dipl. -Ing. agr. Walter Grotz
TU München
Bayerische Landesanstalt für Landtechnik
Abteilung Umwelttechnik der Landnutzung
Am Staudengarten 3
85354 Freising
Tel.: +49/(0)8161/713796
Fax: +49/(0)8161/714546
E-mail: grotz@tec.agrar.tu-muenchen.de

Dipl.-Ing. agr. Barbara Rathmer
TU München
Bayerische Landesanstalt für Landtechnik
Abteilung Umwelttechnik der Landnutzung
Am Staudengarten 3
85354 Freising
Tel.: +49/(0)8161/713792
Fax: +49/(0)8161/714546
E-mail: barbara@tec.agrar.tu-muenchen.de

Dr. agr. Andreas Gronauer
TU München
Bayerische Landesanstalt für Landtechnik
Abteilung Umwelttechnik der Landnutzung
Am Staudengarten 3
85354 Freising
Tel.: +49/(0)8161/713453
Fax: +49/(0)8161/714546
E-mail: gronauer@tec.agrar.tu-muenchen.de

Univ.-Prof. Dr.agr. Dr.h.c. (AE) Hans Schön
Bayer. Landesanstalt für Landtechnik
Vöttinger Str. 36
85350 Freising-Weihenstephan
Tel.: +49/(0)8161/713441
Fax: +49/(0)8161/713895
schoen@tec.agrar.tu-muenchen.de