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Monitoring of Tempreature, Humidity and Air Quality inside Pig Weaner House in Eastern China

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Abstract: To provide reliable data on the indoor environment in livestock buildings, continuous measurements were conducted in two commercial naturally-ventilated pig weaner barns in eastern China. The barn floors were partially-slatted and pig manure was removed daily. Indoor temperature and relative humidity (T and RH), and concentrations of carbon dioxide (CO_2), ammonia (NH_3), hydrogen sulfide (H_2S), and methane (CH_4) were continuously measured with multi-points monitoring for one year. Hourly means of barn T and RH were ranged from 0.9℃ to 42.0℃ and 31.1% to 97.7%, respectively. Hourly mean CO_2, NH_3, H_2S, and CH_4 concentrations were ranged from 423 mg/m^3 to 3 534 mg/m^3, 0.11 mg/m^3 to 49.7 mg/m^3, 0.9 μg/m^3 to 41.7 μg/m^3, and 0.1 mg/m^3 to 17.7 mg/m^3, respectively. The yearly average barn T and RH were (25.6 ± 8.6)℃ (yearly mean ± standard deviation) and (71.4 ± 11.7)%, respectively. The yearly average CO_2, NH_3, H_2S, and CH_4 concentrations were (1 982 ± 744) mg/m^3, (10.9 ± 8.4) mg/m^3, (8.2 ± 5.2) μg/m^3, and (2.9 ± 1.9) mg/m^3, respectively. Diurnal and seasonal variations of T, RH, and gas concentrations were clearly shown. The minimum and maximum hourly mean T and RH, and the maximum hourly mean CO_2 and NH_3 concentrations exceeded the relevant China National Standards for commercial pig weaner barns. However, the maximum H_2S and CH_4 concentrations were at safe levels for animal health and barn safety. The long-term high-frequency monitoring system has been approved as an appropriate technique for assessing air quality and environmental condition in animal building, the results also indicated that piggery housing system design and ventilation system optimizing still need further exploration in eastern China.

Key words: pig weaner house; pig house environment; air quality; online continuous monitoring

0 Introduction

Temperature (T) and relative humidity (RH) in livestock and poultry houses are the basic environmental elements for animal growth. Carbondioxide (CO_2), ammonia (NH_3), hydrogen sulfide (H_2S) and other polluting gases produced by livestock and poultry may negatively affect animal productivity and health conditions, and cause respiratory diseases for farm operators. These pollutants may also result in serious pollution to the natural ecosystems in the area surrounding the farms and hazardous effect on the health of nearby residents. This maylead to strained relationship between the farms and the neighboring residents[1-2]. High concentrations of accumulated methane (CH_4) in the pig houses may cause fire or explosions[3]. Methaneis also a greenhouse gas, which has a potential impact on climate change.

China is one of the biggest countries in the world on livestock and poultry production. With the development of large-scale animal farms and the increase of public awareness of environmental protection, the pollutants concentrations and emissions from animal farms become a major concern[4-6]. Currently, the Chinese pig farms are mainly using open or semi-open animal houses with natural ventilation and manually waste cleaning methods. These are significant differences in comparison with the pig farms in Europe and North America, where many of the pig houses are designed

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with mechanical ventilation and under-floor deep-pit manure storage. Therefore, studies on temperature, humidity and air quality in Chinese pig farms with specific environmental situations are needed.

Investigations on air quality at livestock and poultry farms in Europe and North America have made much progress in pollutants analysis methods and techniques[7], gas release modeling[8], and continuous monitoring equipment[9-14]. SCHOLTENS et al.[7] used external tracer ratio method, internal tracer ratio method and passive flow sampling method to determine and evaluate NH_3 emissions. However, these methods require specific conditions to reach certain accuracies. In 2008, KEENER et al.[8] established a nitrogen balance model for predicting NH_3 emission limits in animal houses with natural ventilation or mechanical ventilation systems. With the development of science and technology, more and more technologies have been applied in this field[9-14]. In recent years, air pollution in livestock and poultry industry in China has received increasing attentions. Relevant research has been carried out. Gas sensor technology[15-16] and photoacoustic infrared analyzer[17] are the major techniques used in gases (e.g., CO_2 and NH_3) monitoring. Compared with gas analyzers, the sensor technology has lower accuracy. However, it is used more widely due to its lower costs. The concentrations of CH_4 and H_2S in livestock and poultry houses were relatively low. Therefore, precision gas detection equipment was necessary for measuring these two gases. For instance, WANG et al.[18] analyzed the greenhouse gases released from the cow feces by using the gas chromatographic method, however, study on in-situ monitoring in the pigsty in eastern China using precision instruments has not yet been found in the literature.

Because the temperature, humidity and air quality in animal buildings vary within 24 h in a day and among different seasons, long-term continuous measurement has become the most reliable and effective research methods. Besides, accurate measurement of air pollutant concentrations in animal buildings is the premise of studying air quality in animal agriculture. However, so far there is still a lack of relevant research on long-term and continuous monitoring and assessment of livestock and poultry environmental parameters. Different pig raising stages require different environmental conditions. In this study, an environmentally sensitive stage of pig raising, the weaned piglet, was selected and a typical farm in eastern China was chosen for data collection. A multi-point continuous monitoring system was used to measure the temperature, relative humidity and concentrations of CO_2, NH_3, H_2S and CH_4 in a weaned piglet house from December 2012 to November 2013. This study is expected to provide new scientific understanding for improving the weaned pig house environment.

1 Materials and methods

1.1 Weaned pig house

The measurements in this study were carried out at a pig farm located in Pujiang County, Zhejiang Province. The farm is a national demonstration base for pig production as it has certain representations on the breeding technology, feeding and management level, house structure, and manure treatment system. Two weaned piglet buildings with identical structure were selected to continuously measure the temperature, humidity and concentrations of main air pollutants. The two weaned piglet buildings are east-west oriented, sharing one side wall. Each house measures 18 m (long) × 7.9 m (wide) × 2.7 m (high). The house floor is half-slatted and the solid partis equipped with hot water heating pipes that are used for heating from December to next March (Fig. 1). Air coolers are used for reducing the temperature in July and August during summer.

There were 16 pens in each building, each with a capacity of approximately 10 weaned piglets during the study. The piglets grew from 7 kg to 30 kg each in the weaned piglet buildings for 35 d to 40 d before being moved out of the house. There was a 7-dnon-occupation time between piglet cycles for house disinfection. The manure was removed manually twice daily. The piglets were fed *ad libitum*.

1.2 Detection methods for indoor and outdoor thermal environment and pollutant concentrations

An outdoor air inlet point, which was close to the center of the south side wall, and an indoor point, which was at the center of the house, were selected in each house for temperature, relative humidity and gases concentration monitoring. All the sampling points were 1 m height as shown in Fig. 1. Because NH_3 concentration gradients exist in the pig houses, choosing 1 m as sampling height was to approach the pig breathing zone and at the same time protect the sampling probes from damaging by the pigs. The sensors and instruments for on-line multi-point air quality monitoring are shown in Fig. 2. They included three T and RH sensors (HS-102S, ±0.5℃, ±3%, Beijing Huakong, China), two T probes (WZP-035, ±0.5 ℃, Shanghai Zhisai, China), two CO_2 sensors (HS102 CO_2, ±3% FS, Beijing Huayang, China), five NH_3 sensors (HSTL NH_3 1009, ±3% FS, Beijing Huakong, China), a H_2S analyzer (TEI 450i, ±1%, Thermo, USA) and a CH_4 analyzer (TEI 55i, ±1%, Thermo, USA).

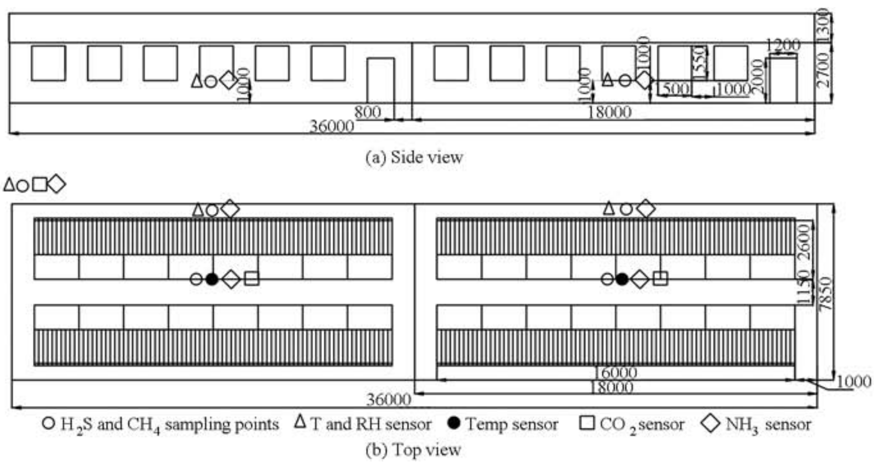


Fig. 1 Schematic diagram of weaner house with measurement and sampling locations

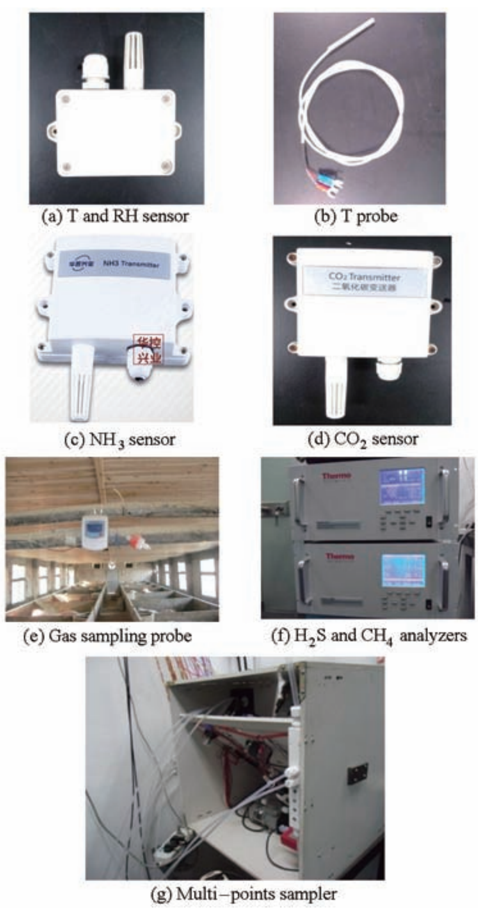


Fig. 2 Sensors, analyzers, and sampling equipment for on-site environmental monitoring

All the sensors and probes were installed in fixed locations except for the CH_4 analyzer and H_2S analyzer. The CH_4 analyzer and H_2S analyzer were connected to a multi-point gas sampler and used software called AirDAC to automatically switch among the five sampling points. Each point was sampled for 10 min before switching to the next one for CH_4 and H_2S concentration analysis.

The AirDAC acquired all the voltage output signals from the sensors and analyzers every sec, converted the signals into engineering units, calculated 60 1-Hz data into 1-min average, and saved the average in a field computer.

1.3 Data analysis method

During data processing and analysis, the invalid monitoring data due to sensor failures and during house cleaning and disinfection period were removed. Microsoft Excel was used to calculate hourly averages, which were employed for all subsequent calculations, statistical analysis, and figure plotting. Daily variations of gas concentrations were analyzed using continuous 5 days of observations in each season, including April 13^{th} – 17^{th} for spring, July 23^{rd} – 27^{th} for summer, October 13^{rd} – 17^{th} for autumn (due to a CH_4 analyzer problem, the CH_4 concentrations from September 1^{st} to 6^{th} were used instead), January 23^{rd} – 27^{th} for winter.

The monthly variations of environmental parameters and gases concentrations were compared by using box-whisker plot. The box-whisker plot presented the average values, median values, 50% quartiles, which were showed as the upper and the lower side lines on the box, and maximum and minimum values, which were expressed with end lines on the whisker.

2 Results and discussion

2.1 Indoor temperature and relative humidity

Monthly variations of indoor temperature and relative humidity are shown in Fig. 3. Hourly average temperatures from 4392 valid measurements during the year are displayed in Fig. 3a. Based on the hourly average data, the yearly average temperature was (25.6 ± 8.6)℃, the minimum and maximum value were 0.9℃ in February and 42.0℃ in August, respectively; and the indoor lowest and highest monthly average temperatures were (13.3 ± 5.7)℃ in February and (34.7 ± 2.8)℃ in July, respectively. According to the Chinese National Standards (GB/T 17824.3—2008)[19], the comfortable environment temperature range for weaned piglets is 20℃ to 25℃, and the extreme temperature range is 16℃ to 28℃. In this study, 64% and 47% of the hourly average temperatures exceeded 25℃ and 28℃, respectively, while 25% and 17% of the hourly temperatures were below 20℃ and 16℃, respectively. The results demonstrated that the floor heating system and air cooling system were still far from meeting the indoor environment requirements for weaned piglets, because the actual minimum temperature in winter was much lower and the maximum temperature in summer was significantly higher than the required environmental temperatures for weaned piglets. Therefore, indoor environment control strategies for weaned piglet houses still need to be further studied and improved.

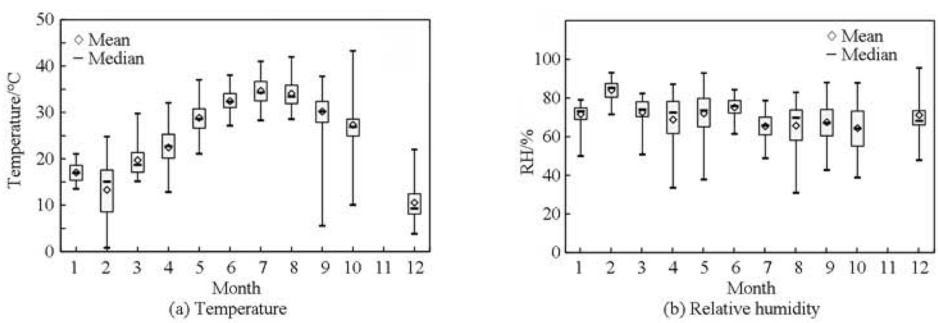


Fig. 3 Monthly variations of temperature and relative humidity in the weaner house No. 1

As shown in Fig. 3b, the yearly average RH was (71.4 ± 11.7)%. The lowest hourly mean RH of 31.1% occurred in August and the lowest monthly average RH of (65.5 ± 6.5)% was observed in July. Correspondently, the highest hourly mean RH of 97.7% happened in December and the highest monthly average RH of (84.1 ± 4.6)% was measured in February. According to the Chinese National Standards[19], the comfortable environmental RH range for weaned piglets is 60% to 70%, and the extremes are 50% and 80%. The results of this study showed that only 24% of the hourly mean RH in the year was in the suggested comfortable range, while 73% of the hourly mean RH was out of the extreme value range, and 59% of the hourly mean RH was higher than 70%. Therefore, the RH in a typical weaned pig house in eastern China was relatively higher than the animals' comfort requirement. This may lead to high body temperature, which could affect the metabolism of animals and reduce the feed conversion rate and daily gain. Consequently, the control of RH in weaned piglet houses was as important as control of temperature.

2.2 CO_2 concentrations in pig houses

As shown in Fig. 4a, the 24 h variations of CO_2 mass concentrations in weaned piglets building were presented with five consecutive days of measurements in each of the four seasons. It can be observed that the indoor CO_2 concentrations started to increase at 7:00 and reached a peak at about 14:00, then gradually declined to the bottom at about 4:00 to 6:00 in the next day. The main source of the indoor CO_2 is the animal breath and the organic compounds degradation in the manure. The animal activity during the daytime was greater than that during the night, therefore, there could be an increase of animal exhalant CO_2. This

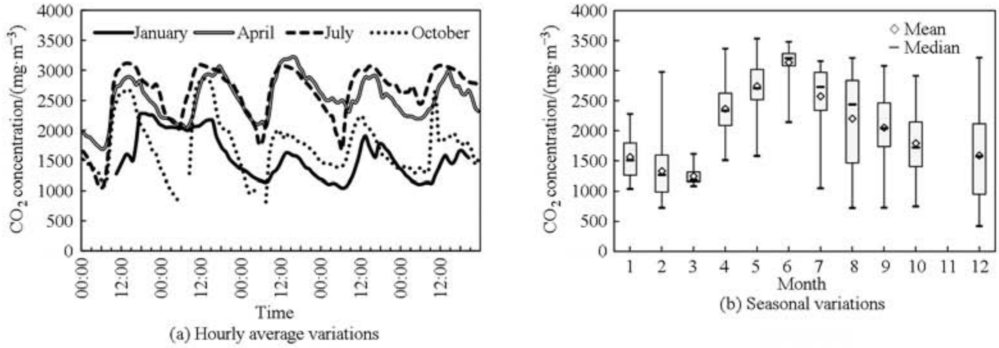


Fig. 4 CO_2 concentration variations in weaner house No. 1

could explain that the CO_2 concentrations tended to increase during the daytime.

The seasonal variation of CO_2 concentrations in the weaned piglet building was presented in the Fig. 4b. The highest hourly average CO_2 concentration occurred in May. This might becaused by the increase of animal activity as the temperature increased, and the increase of O_2 consumption and exhaled CO_2. Meanwhile, the temperature rising could increase the aerobic microorganism activity and accelerate the organic compounds decomposition. However, in July and August with the highest temperature, the indoor CO_2 concentrations decreased due to the increasing in ventilation rates for house cooling. In winter, although the ventilation rates decreased, organic matter degradation rates also decreased along with temperature decreasing. Therefore, the CO_2 concentrations in winter were lower than those in summer. High CO_2 concentrations can cause disease symptoms such as chronic hypoxia, listlessness, anorexia, and slower growth rate. In the Chinese National Standards[19], CO_2 concentrations must be under 1 300 mg/m^3. The yearly average CO_2 concentration was (1 982 ± 744) mg/m^3 calculated from 3 931 hourly mean data, which ranged from 423 mg/m^3 to 3 534 mg/m^3; and 78% of which exceeded the suggested range. The periods exceeding the standard limit mainly occurred in spring, summer, and in the daytime in fall. In order to avoid potential risks and ensure the normal growth of weaned piglets, it was suggested to increase the ventilation rate during spring, summer and from 12:00 – 15:00 in fall when the CO_2 concentrations are high.

2.3 NH_3 concentrations in pig houses

The hourly variations of NH_3 concentrations in the weaned piglets building during the five consecutive days in the four seasons are shown in Fig. 5a. The NH_3 concentrations were relatively low from 8:00 to 12:00. Higher concentrations were observed from 17:00 to 21:00. The fact that the average NH_3 concentrations maintained a relatively higher level during night was because the ventilation rate was reduced during night to ensure the proper temperature. If the temperature varied too much, it might cause diarrhea for weaned piglets as they were sensitive to temperature[21]. On the other hand, increasing in animal activity during the daytime could enhance their metabolism, generate more waste and result in a higher indoor NH_3 concentrations. The highest detected NH_3 concentration was 49.7 mg/m^3, while the lowest was 0.11 mg/m^3, and the mean value was 10.9 mg/m^3.

The seasonal variations of NH_3 concentrations in weaned piglets building are shown in the Fig. 5b. The

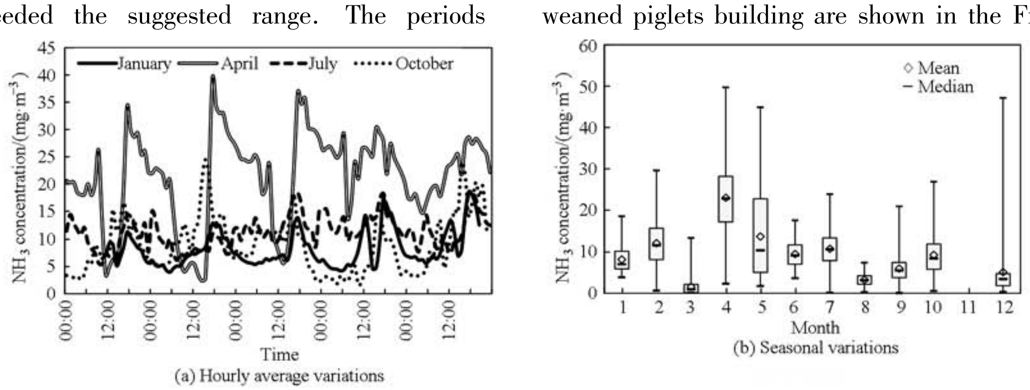


Fig. 5 NH_3 concentration variations in weaner house No. 1

NH_3 concentrations were relatively lower during Summer (June to September), and the lowest value was (3.3 ± 1.4) mg/m^3 obtained in August. This is contrary to the trend of CO_2 because these two gases were originated from different sources. Ammonia is mainly from urea decomposition catalyzed by urease. While, the main source of CO_2 is from pig respiration and only small proportion of CO_2 is from manure degradation[21-22]. High NH_3 concentrations occurred in April (monthly average concentration was (23.0 ± 9.0) mg/m^3). This was because the outdoor temperature increased from winter to spring (the average T was 22.5℃ in April), causing an increase in the urease activity and an accelerating of manure decomposition, and resulting in an increasing of NH_3 concentrations. In spring with a relative comfortable temperature, nature ventilation was used at the farm. With the increasing in temperature in summer, more NH_3 was originated from the manure degradation. However, when ventilation rate was increased to lower the temperature, it also resulted in a decrease in NH_3 concentration in summer compared with spring. In poorly ventilated environment, the NH_3 generated from manure will accumulate and increase its concentrations in the pig house. Usually, NH_3 concentrations should be kept below 8 mg/m^3 to 20 mg/m^3. When it reached 23 mg/m^3 to 38 mg/m^3, it may cause respiratory tract infection (i.e., cough and dizziness) of farm operators. The results of this study showed that the yearly average NH_3 concentration was (10.9 ± 8.4) mg/m^3 based on 4 201 hourly average data. The time of NH_3 over 8 mg/m^3 and 20 mg/m^3 reached 27% and 6%, respectively, which did not fully meet the requirements of NH_3 concentration. Therefore, based on this finding, it was suggested that air pollution treatment measures be considered in the houses.

2.4 H_2S concentrations in pig houses

The daily variations of average H_2S concentrations in weaned piglets building are shown in Fig. 6a. Different from CO_2 and NH_3, the H_2S concentrations did not show an obvious diurnal variation, but more fluctuation. The 20 days of data shown in Fig. 6a as an example demonstrated that there existed 31% to 81% variations between the lowest and the highest hourly average value during a day, and instantaneous difference was even greater. NI et al.[24] proposed a Bubble-release model to explain H_2S variation because H_2S has a low solubility (0.34 g/(100 g) in water at standard atmosphere and 25℃) and is easily supersaturated in the liquid. Therefore H_2S can exist as bubbles in the liquid manure. These bubbles can go through collision and agglomeration to increase their sizes and buoyant forces, and finally burst from the liquid manure surface into the air when disturbance occurred. The generation of such bubbles is irregular. However, the Bubble-release model is only applicable to long-term stored manure (over 10 days). In this study, the manure was cleaned every day, so the irregular H_2S concentration change may be caused by other unknown factors.

The seasonal variation of H_2S concentrations in the weaned piglet building are presented in Fig. 6b. The highest monthly and hourly average values were (18.2 ± 1.4) $\mu g/m^3$ (February) and 41.7 $\mu g/m^3$ (September), respectively. The lowest monthly and hourly average values were (8.2 ± 1.5) $\mu g/m^3$ (October) and 0.9 $\mu g/m^3$ (December), respectively. The results of this study also showed that the H_2S concentrations were relatively higher in winter because the cleaning frequency was decreased in winter and the accumulated manure in the piglet building was more than other seasons. Besides, the use of the heating

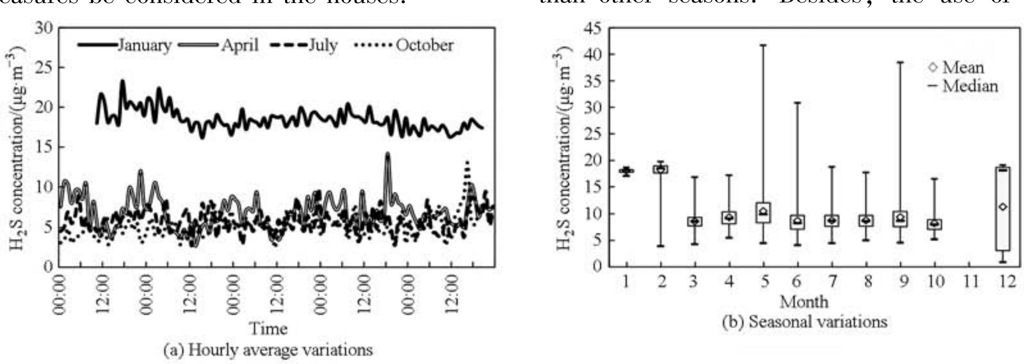


Fig. 6 H_2S concentration variations in weaner house No. 1

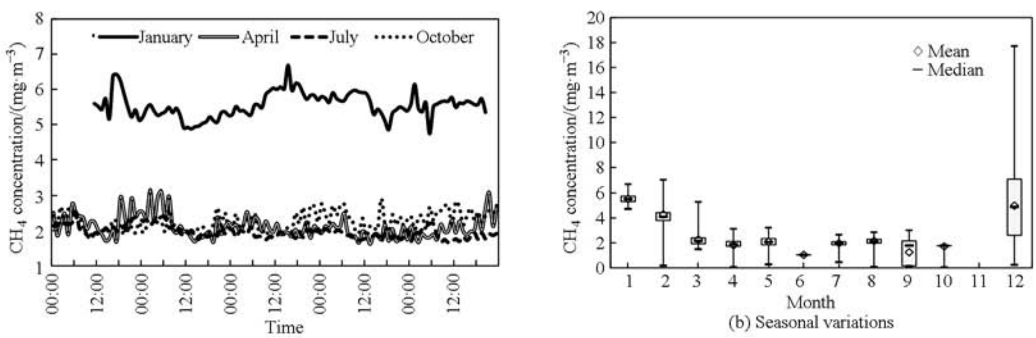
system could accelerate the release of H_2S and the decrease of ventilation rate could also cause the indoor accumulation of H_2S.

The national standards require that the H_2S concentrations be within 8 mg/m^3. NI et al.[25] reported that H_2S concentrations in pig houses with mechanical ventilation and deep-pit manure storage system without manure disturbance were normally lower than 1.5 μg/m^3. Stored manure stirring may cause the surrounding H_2S concentrations in the pit reaching the lethal threshold[26]. From the air quality point of view, the H_2S concentrations in the weaned piglet houses (the yearly average was (8.2 ± 5.2) μg/m^3) were significantly lower than the Chinese National Standards and the concentrations reported in pig houses with deep-pit manure storage systems. However, the use of high sulfur content water at the farm could significantly increase the H_2S release from manure[27] and increase the indoor H_2S concentrations. Therefore, even using the similar house design and management, studies on the H_2S concentrationsin weaned piglet houses in other areas may be possible to observe higher concentrations than those in this study.

2.5 CH_4 concentrations in pig houses

The daily variation curves of hour average of CH_4 mass concentration in weaned pig building are shown in Fig. 7a. The average mass concentrations in April, July and September were all lower than 3.6 mg/m^3. But the diurnal variations were not obviously shown. The highest average concentration in January was detected at around 18:00. Subsequent decreasing in concentrations might be caused by manure-cleaning operation from 07:00 to 09:00 each day. The mass concentration of CH_4 dropped after cleaning, and then increased gradually till the night. Its main reason was that accumulation of the new generated manure after the cleaning could produce a partial anaerobic condition, in which the methanogens could decompose the fecal organic matters to generate CH_4.

The seasonal variation of CH_4 mass concentrations in weaned piglets building are shown in Fig. 7b. The highest CH_4 mass concentration was obtained in winter. The monthly average concentrations were (4.8 ± 2.9) mg/m^3, (5.6 ± 0.4) mg/m^3 and (4.5 ± 1.1) mg/m^3 in December, January and February, respectively. Relatively lower concentrations were found inspring and fall. They were (1.8 ± 0.6) mg/m^3 and (1.7 ± 0.3) mg/m^3 in April and October, respectively. Different from the NH_3 concentrations, which were the lowest in summer, the CH_4 concentrations were higher in summer than those in spring and fall. The main reason was that the optimum temperature for methanogens activity was between 30℃ and 65℃. Therefore, more CH_4 could be generated from the organic matter decomposition at higher temperatures in summer.



(a) Hourly average variations　　(b) Seasonal variations

Fig. 7　CH_4 concentration variations in weaner house No. 1

At present, there is no national standard in China for CH_4 mass concentration for large-scale pig farms. There is also lack of international reports related to the effect of CH_4 on health of animals. However, reported fire accidents at pig farms were usually caused by a large amount of bubbles with combustible gases (contains 50% ~ 70% of CH_4) released from the under-floor manure pit. The results of this study showed that CH_4 concentrations in the weaned pig houses (yearly average was (2.9 ± 1.9) mg/m^3) was only 1/100,000 of the CH_4 combustible concentration. This was consistent with the results of other studies; for example, DONG et al.[28] reported that the yearly average concentration of CH_4 from a pig farm in Beijing was 6.6 mg/m^3. There is no evidence showing that these concentrations are potentially harmful to weaned piglets.

3 Conclusions

From the-year continuous monitoring of temperature, humidity and mass concentrations of CO_2, NH_3, H_2S and CH_4 in the weaned piglet houses, the following conclusions were drawn:

(1) Although the heating pipes and the air coolers were used to adjust the temperature in the weaned piglet buildings, the lowest and highest hourly average temperature in the year were still reach to 0.9 and 42.0℃, respectively, which exceeded the range of suitable temperatures for piglets. The lowest and highest hourly average RH in the year were 97.7% and 31.1%, respectively, which also exceeded the range set by the Chinese National Standard. These extreme thermal environment conditions were not favorable for pig health.

(2) The CO_2 concentrations during daytime were higher than during night. The highest mass concentration of CO_2 (3 534 mg/m^3) appeared in May and exceeded the upper limit of the Chinese National Standard. During the practical operating, it is necessary to adopt measures (i. e., increase the ventilation rate) to reduce CO_2 concentrations during high CO_2 release periods.

(3) The NH_3 concentrations in the afternoon and evening were higher than in the morning. They were higher in winter than in other seasons. The highest hourly average mass concentration was 49.7 mg/m^3, which was three times of the threshold set in the Chinese national standard. Therefore, relevant treatment measures will be needed.

(4) Because the manure was cleaned manually, the mass concentrations of H_2S and CH_4 were relatively low and not harmful to the pig growth and the building safety.

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华东地区典型保育猪舍温湿度和空气质量监测

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摘要: 为探究畜禽舍温湿度与空气质量情况,获得较可靠的监测数据,并为畜禽舍环境改善提供依据,以华东地区某典型规模猪场的两间自然通风保育猪舍为对象,应用多点连续监测方法对猪舍内的温湿度以及主要污染气体(二氧化碳(CO_2)、氨气(NH_3)、硫化氢(H_2S)和甲烷(CH_4))的质量浓度进行了为期1年的监测。监测结果显示,该保育猪舍内温度、相对湿度以及CO_2、NH_3、H_2S、CH_4质量浓度的小时平均值范围分别为0.9~42.0℃、31.1%~97.7%、423~3 534 mg/m^3、0.11~49.7 mg/m^3、0.9~41.7 μg/m^{3}和0.1~17.7 mg/m^3;对应的(年平均值±方差)分别为(25.6±8.6)℃、(71.4±11.7)%、(1 982±744) mg/m^3、(10.9±8.4) mg/m^3、(8.2±5.2) μg/m^{3}和(2.9±1.9) mg/m^3。研究结果还揭示了这些指标每日和四季的变化规律以及舍内环境状况。全年的最低和最高小时平均温度和相对湿度,以及小时平均最高CO_2和NH_3质量浓度超出了国家标准中规定的规模猪场环境参数的临界值。但舍内的H_2S和CH_4质量浓度很低,不会对猪的健康生长以及猪舍的安全造成危害。

关键词: 保育猪舍; 猪舍环境; 空气质量; 在线连续监测

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Monitoring of Tempreature, Humidity and Air Quality inside Pig Weaner House in Eastern China

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Abstract: To provide reliable data on the indoor environment in livestock buildings, continuous measurements were conducted in two commercial naturally-ventilated pig weaner barns in eastern China. The barn floors were partially-slatted and pig manure was removed daily. Indoor temperature and relative humidity (T and RH), and concentrations of carbon dioxide (CO_2), ammonia (NH_3), hydrogen sulfide (H_2S), and methane (CH_4) were continuously measured with multi-point monitoring for one year. Hourly means of barn T and RH ranged from 0.9℃ to 42.0℃ and 31.1% to 97.7%, respectively. Hourly mean CO_2, NH_3, H_2S, and CH_4 concentrations ranged from 423 mg/m^3 to 3 534 mg/m^3, 0.11 mg/m^3 to 49.7 mg/m^3, 0.9 μg/m^3 to 41.7 μg/m^3, and 0.1 mg/m^3 to 17.7 mg/m^3, respectively. The yearly average barn T and RH were (25.6±8.6)℃ (yearly mean ± standard deviation) and (71.4±11.7)%, respectively. The yearly average CO_2, NH_3, H_2S, and CH_4 concentrations were (1 982±744) mg/m^3, (10.9±8.4) mg/m^3, (8.2±5.2) μg/m^3, and (2.9±1.9) mg/m^3, respectively. Diurnal and seasonal variations of T, RH, and gas concentrations were clearly shown. The minimum and maximum hourly mean T and RH, and the maximum hourly mean CO_2 and NH_3

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concentrations exceeded the relevant China National Standards for commercial pig weaner barns. However, the maximum H_2S and CH_4 concentrations were at safe levels for animal health and barn safety. The long-term high-frequency monitoring system was approved as an appropriate technique for assessing air quality and environmental condition in animal building. The results also indicated that piggery housing system design and ventilation system optimizing still need further exploration in eastern China.

Key words: pig weaner house; pig house environment; air quality; online continuous monitoring

引言

畜禽养殖场舍内温湿度是畜禽生长环境的基本要素。畜禽养殖场产生的二氧化碳(CO_2)、氨气(NH_3)、硫化氢(H_2S)等污染气体不仅有可能导致畜禽生产效率和健康水平降低、养殖工人呼吸系统产生疾病等一系列问题,而且对养殖场及周围生态环境也会造成严重的污染,危及附近居民的健康,并可能导致养殖场与周围居民关系紧张[1-2]。养猪场内积累的高浓度甲烷(CH_4)有可能引发猪舍火灾和爆炸[3]。甲烷还是一种温室气体,对气候变化有潜在影响。

中国是世界畜禽养殖大国,随着畜禽养殖业向规模化发展和公众环保意识的增强,养殖场污染气体的浓度及排放问题备受关注[4-6]。目前中国猪舍多为开放或半开放式、以自然通风和人工清粪方式为主,与欧美主要以密封、机械通风、水泡粪方式为主的猪舍差异较大,因此亟待开展基于中国养殖特点的猪舍内温湿度及空气质量的监测研究。

欧美畜禽养殖场空气质量相关研究已在污染气体分析方法与手段[7]、释放模型[8]、连续监测设备与方法[9-14]等方面取得一定成果。如2004年,SCHOLTENS等[7]采用外部示踪比法、内部示踪比法和被动流量抽样法来测定评估氨气排放情况,然而这些方法需要在一定条件下才能确保精度。KEENER等[8]于2008年建立了一种基于氮平衡的NH_3模型来预测自然通风和机械通风情况下的NH_3排放上限。随着科技的进步,越来越多的技术开始应用于这一领域[9-14]。近几年,畜禽业空气污染研究在中国越来越受到重视,且相关探究逐步展开。在污染气体(如CO_2和NH_3)检测方法上主要是采用气体传感器技术[15-16]和光声红外气体分析仪[17]等。与气体分析仪相比,传感器技术虽然精度较低,但费用小的优点使其具有更广泛的应用。畜禽舍内的H_2S、CH_4等浓度较低,需要采用精密的气体监测设备对其进行测量,例如王效琴等[18]采用气相色谱法分析了奶牛粪便中的温室气体,但是猪舍内的精密仪器监测研究还未见报道。

因畜禽舍内温湿度及空气质量在每天24 h内以及不同季节之间均有变化,故长期连续测量便成为最可靠和有效的研究方法,而精确地检测畜禽场空气污染物的浓度则是开展畜牧业空气质量研究的前提。但是目前国内长期连续监测畜禽环境并进行评估的相关研究还较少。由于不同阶段的猪只对环境要求不同,本文选择我国华东地区典型规模猪场中对环境敏感的断奶仔猪保育舍为检测对象,应用多点连续监测方法对保育猪舍内的温湿度及CO_2、NH_3、H_2S、CH_4等主要污染气体质量浓度进行为期1年(从2012年12月到2013年11月)的监测,以期为改善保育猪舍内环境提供科学依据。

1 研究对象与方法

1.1 保育猪舍

本研究监测的猪舍所在猪场位于浙江省浦江县,是国家级生猪养殖示范基地,该猪场的养殖工艺、饲养管理水平、畜禽舍结构、废弃物猪粪处理等方面在浙江省及我国华东地区有一定的代表性。研究选取其中2间结构完全相同的保育猪舍作为舍内温湿度及主要污染气体质量浓度连续监测的对象。保育猪舍为东西走向,共用单侧墙体,每间建筑尺寸为:18.0 m(长)×7.9 m(宽)×2.7 m(吊顶至地面高度),地面为半漏缝地板形式,实心部分铺设热水加热管网(图1)。每间猪舍共计16个猪栏,平均每栏养猪数量约为10头,舍内饲养断奶仔猪体重范围为7~30 kg,转群周期为35~40 d,转群消毒间隔时间为7 d。猪舍夏季采用冷风机降温,主要在7、8月份使用;冬季采用实心地面下的热水管网加温,主要在当年12月份到次年3月份使用;常年采用2次/d的人工清粪方式,并提供保育仔猪自由采食和饮水。

1.2 猪舍内外热环境和污染气体浓度检测方法

保育猪舍的温湿度和污染气体浓度监测点分布于舍外进风口位置以及舍内南侧靠墙和中间位置;采样点均离地1 m,具体布局如图1所示。猪舍中存在氨气浓度梯度。选择1 m高度主要是为了既比较接近猪的呼气区域,又能保护采样头不被猪损坏。在线多点空气污染连续监测系统中采用的环境参数

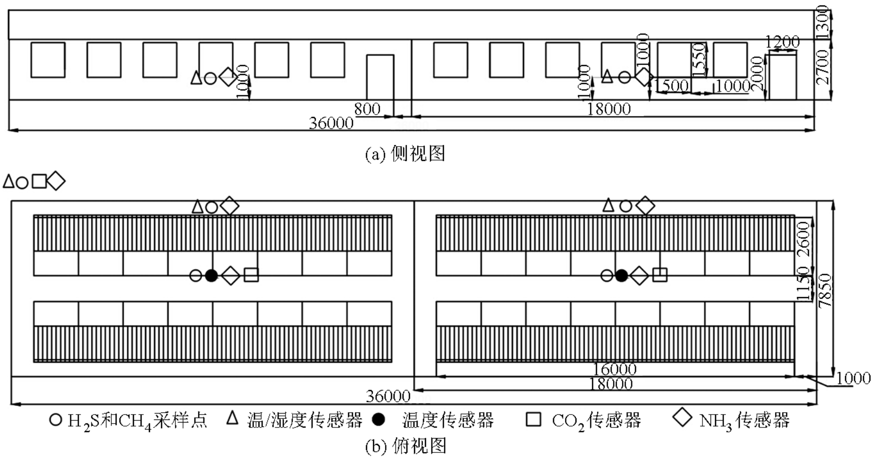


图 1　猪舍结构与监测点分布示意图

Fig. 1　Schematic diagram of structure of weaner house and sampling locations

图 2　现场环境参数检测使用的仪器和设备

Fig. 2　Instruments and equipments for on-site environmental monitoring of parameters detection

检测仪器和设备如图 2 所示，主要包括：3 个温湿度传感器（HS－102S 型，精度 ±0.5℃、±3%，北京华控，中国）、2 个温度探头（WZP－035 型，精度 ±0.5℃，上海置赛，中国）、2 个 CO_2 传感器（HS102CO_2型，精度 ±3% FS，北京华阳，中国）、5 个 NH_3传感器（HSTL$NH_3$1009 型，精度 ±3% FS，北京华控，中国）、1 台 H_2S 分析仪（TEI 450i 型，精度 ±1%，赛默飞世尔，美国）和 1 台 CH_4分析仪（TEI 55i 型，精度 ±1%，赛默飞世尔，美国）。

除了 H_2S 分析仪和 CH_4分析仪以外，所有传感器都安装在固定地点进行连续测量。而 H_2S 分析仪和 CH_4 分析仪则连接到一台多点气体采样器（图 2g），由 AirDAC 控制实现 5 个采样点的仪器分享（图 1）。气体采样器每次只从一个采样点抽取气体样品，给 2 台分析仪连续提供 10 min 气样，然后切换到下一个采样点。

所有在线传感器和分析仪输出的电压信号，均由 AirDAC 进行频率为每秒一次的数据采集。每分钟的 60 个数据由 AirDAC 转换成物理量值，并预处理后取平均值，储存于现场计算机。

1.3　数据分析方法

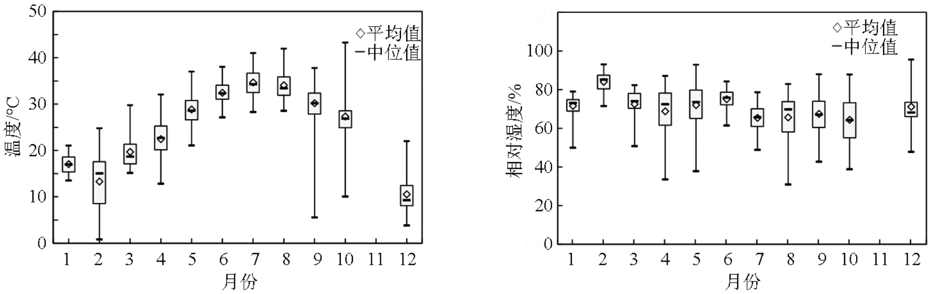
数据分析时首先剔除因传感器故障、监测期间猪转群后清理消毒期的无效数据，再通过 Excel 计算出小时平均值。所有后续计算、统计分析及数据图表数据均基于小时平均值。气体浓度日变化以每季度连续 5 d 有效检测数据为例进行分析，其中，春季代表日期为 4 月 13 日—4 月 17 日，夏季为 7 月 23 日—7 月 27 日，秋季为 10 月 13 日—10 月 17 日（因 CH_4仪器故障，秋季 CH_4数据为 9 月 1 日—9 月 6 日），冬季为 1 月 23 日—1 月 27 日。环境参数及污染气体浓度的月变化采用盒型图进行对比，以分析全年季节性差异；该盒型图数据包括平均值、中位值、盒子上下边所表示的上下四分位数、上触须线端点表示的最大值及下触须线端点表示的最小值。

2　结果与讨论

2.1　猪舍温湿度

猪舍温度与湿度月变化如图 3 所示。图 3a 对一年所测的 4 392 h 温度平均值有效数据分析结果表明：全年保育猪舍年平均温度为（25.6 ±8.6）℃，

保育猪舍温度小时平均最低值和最高值分别为0.9℃(2月份)和42.0℃(8月份);而舍内最低和最高(月平均值±方差)分别为(13.3±5.7)℃(2月份)和(34.7±2.8)℃(7月份)。根据国家标准[19],保育猪较为适宜的环境温度为20~25℃,最低和最高温度分别为16℃和28℃。本研究监测结果显示,超过25℃和28℃的时段分别占到了64%和47%,而低于20℃和16℃的时段分别占25%和17%,由此可见,目前猪舍所采用的冬季地暖水保温和夏季冷风机降温的措施仍不能完全满足保育猪适宜环境温度的要求,冬季时最低气温远低于保育猪对环境温度的需求,夏季时最高舍内温度也明显高于猪体能承受的最高温度。因此,保育猪舍环境调控相关的措施还有待进一步研究和完善。



(a) 温度 (b) 相对湿度

图3 保育猪舍温湿度的月变化规律(以1号舍为例)

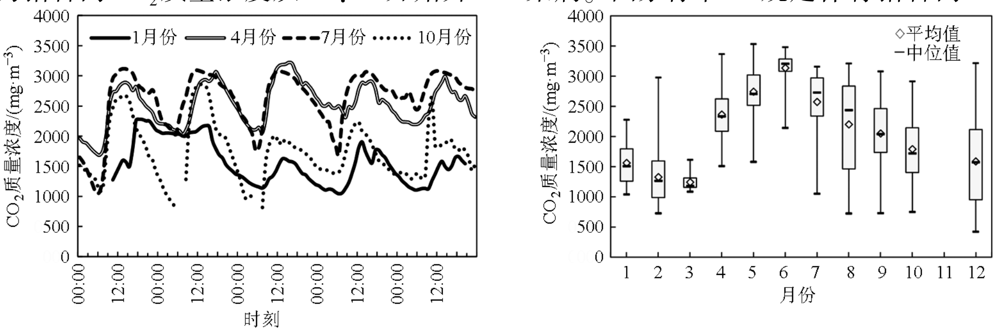
Fig. 3 Monthly variations of temperature and relative humidity in weaner house No. 1

图3b所示,保育舍全年相对湿度平均值为(71.4±11.7)%,而小时平均最低值为31.1%(8月份),(月平均最低值±方差)为(65.5±6.5)%(7月份);小时平均最高值为97.7%(12月份),(月平均最高值±方差)为(84.1±4.6)%(2月份)。国家标准的保育舍舒适范围相对湿度为60%~70%,最低和最高临界值分别为50%和80%[19]。结果显示,仅24%的时段达到了舒适范围要求,73%的时段达到了临界值要求,而其中高于70%湿度的时段达到了59%,因而,中国华东地区典型猪舍相对湿度较动物舒适环境所需湿度偏高,这可能导致动物夏季体温过高、影响动物代谢、降低饲料转化率和日增重等。因此,保育猪舍的湿度调控需求与温度同样重要,本研究中的保育猪舍有待采用更有效可行的湿度调控技术。

2.2 猪舍 CO_2 质量浓度

如图4a所示,由4个季度中连续5 d的小时平均值可以看出保育猪舍内 CO_2 质量浓度24 h的变化。其规律为猪舍内 CO_2 质量浓度从07:00开始升高并在14:00左右达到最高点,而后逐渐降低,并在凌晨04:00—6:00达到最低值。猪舍内 CO_2 的来源主要是猪的呼吸排放和猪粪尿中有机质的降解释放。猪舍内 CO_2 变化规律主要与这些来源有关:仔猪在白天的活动量大于夜间,呼出的 CO_2 量明显增加。所以,CO_2 的质量浓度会出现白天增高的趋势。

保育猪舍 CO_2 季节变化规律如图4b所示。保育猪舍内 CO_2 小时平均最高质量浓度出现在5月份,这可能是猪只随着温度的升高而活动增强,消耗的 O_2 和呼出的 CO_2 增多,同时温度上升可增加好氧微生物活性,加快有机物质分解速率,产生较多的 CO_2;而在7月份至8月份最炎热季节,猪舍内为降温采取增大通风量的措施,从而导致猪舍 CO_2 质量浓度有所下降。进入冬季以后,尽管通风量下降,但猪排泄物有机质降解速率也随温度降低而下降,因而舍内 CO_2 的质量浓度呈现出低于夏季月份的情况。猪舍内 CO_2 含量如过高,猪会出现慢性缺氧、精神萎靡、食欲下降、增重缓慢等症状,易感染各类传染病。国家标准[19]规定保育猪舍内 CO_2 质量浓度



(a) 小时平均值日变化 (b) 季节变化

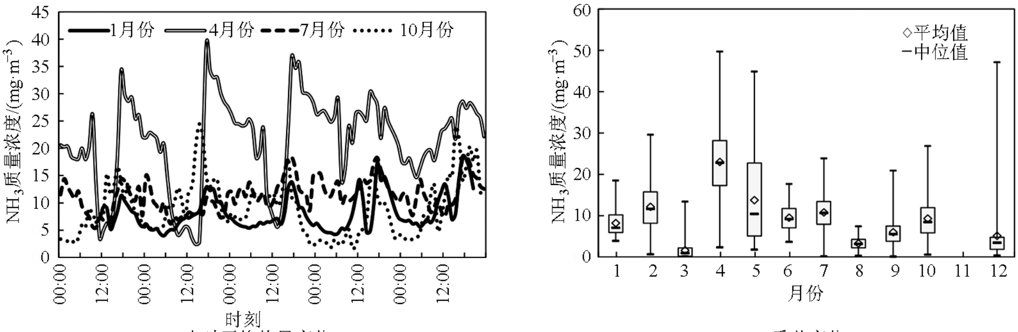
图4 保育猪舍 CO_2 变化规律(以1号舍为例)

Fig. 4 CO_2 concentration variations in weaner house No. 1

不应超过 1 300 mg/m³。参照这个标准,基于全年有效的 3 931 个 CO_2 质量浓度小时平均值数据(平均值为(1 982 ± 744) mg/m³,质量浓度变化区间为 423 ~ 3 534 mg/m³),超过国家标准质量浓度的时段占到了 78%,主要发生在春、夏季以及秋季的白天时段。为避免潜在风险,保证保育猪生长发育,在生产管理上需要对应高 CO_2 浓度时段采取增加通风量等措施,根据本研究结果,建议春、夏季全天以及秋季的 12:00—15:00 增加舍内通风。

2.3　猪舍 NH_3 质量浓度

保育舍每个季节连续 5 d 的小时平均 NH_3 质量浓度变化规律如图 5a 所示。一天中平均浓度较低的情况出现在 08:00—12:00,较高的情况出现在 17:00—21:00。夜间平均质量浓度持续维持在较高的水平,这是由于仔猪对温度变化比较敏感,如果温度变动过大或过低,仔猪会出现腹泻症状[20],所以为保证舍内适宜温度,夜间保育舍通风量较低。而仔猪在白天的活动量加大,新陈代谢增强,排泄物量增加,进而室内 NH_3 的质量浓度较夜间高。保育猪舍的 NH_3 小时平均质量浓度统计结果显示最大质量浓度为 49.7 mg/m³,最小质量浓度为 0.11 mg/m³,平均质量浓度为 10.9 mg/m³。

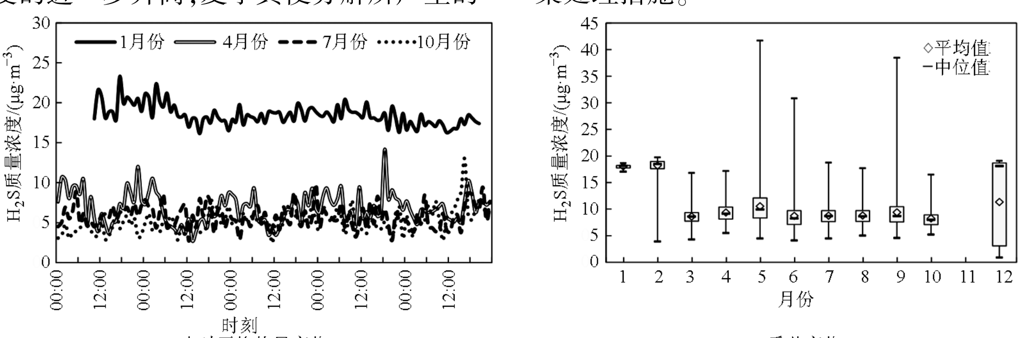


(a) 小时平均值日变化　　(b) 季节变化

图 5　保育猪舍 NH_3 质量浓度变化规律(以 1 号舍为例)

Fig. 5　NH_3 concentration variations in weaner house No. 1

NH_3 质量浓度的季节变化如图 5b 所示,夏季(6—9 月份)的 NH_3 质量浓度相对较低,其中,NH_3 月平均质量浓度最低值((3.3 ± 1.4) mg/m³)出现在 8 月份。这与 CO_2 的趋势相反,主要原因是二者的主要来源不同。猪舍内 NH_3 主要来自于猪群每天排出的尿液中的尿素在脲酶催化作用下的分解。猪舍中 CO_2 主要由猪的呼吸产生,而由粪尿所产生的只占一小部分[21-22]。较高的 NH_3 质量浓度出现在 4 月份(月平均质量浓度为(23.0 ± 9.0) mg/m³)。这是由于随着冬季到春季气温不断上升,4 月份平均气温达到 22.5℃(图 3a),使得脲酶活性较强,尿素分解速率增加,从而使 NH_3 质量浓度上升,由于此时温度为动物舒适温度范围,猪场一般采取自然通风;随着温度的进一步升高,夏季粪便分解所产生的 NH_3 尽管有所增加,但是由于降温需求而增加通风量使得 NH_3 及时排出,因而夏季舍内浓度较春季低。在未良好控制猪舍通风的情况下,粪尿分解产生的大量 NH_3 将在舍内不断蓄积,浓度逐渐升高。通常,保育舍内空气中 NH_3 质量浓度应控制在 8 ~ 20 mg/m³ [19,23];当 NH_3 质量浓度达到 23 ~ 38 mg/m³ 时,有可能诱发舍内工作人员呼吸道病原感染,引起咳嗽、喘气。本项目监测结果表明,保育舍 NH_3 质量浓度全年小时平均值超过 8 mg/m³ 和 20 mg/m³ 的时段分别占 27% 和 6%(总有效小时平均值数据量为 4 201 个,年平均质量浓度为(10.9 ± 8.4) mg/m³),不能完全满足 NH_3 质量浓度控制的要求,由此,生产中应结合 NH_3 质量浓度监测结果采取相应的空气污染处理措施。



(a) 小时平均值日变化　　(b) 季节变化

图 6　保育猪舍 H_2S 质量浓度变化(以 1 号舍为例)

Fig. 6　H_2S concentration variations in weaner house No. 1

2.4 猪舍 H_2S 质量浓度

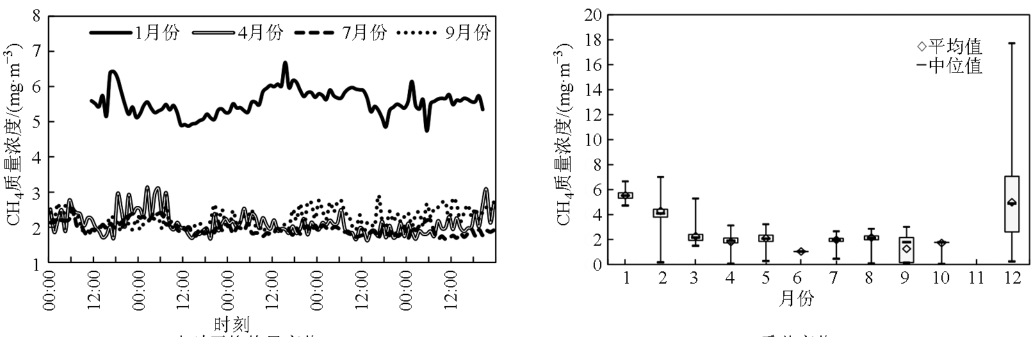
图6a是保育舍内 H_2S 质量浓度小时平均值的日变化规律。与 CO_2 和 NH_3 不同，H_2S 质量浓度并未表现出明显的昼夜变化，然而其波动更为频繁，以图6a中选取的20 d为例，每日最高小时平均值与最低平均值之间的变化率达到31% ~81%，而瞬时浓度差更高。NI等[24]提出了气泡释放模型(Bubble-release model)来解释 H_2S 气体浓度在短时间内产生的巨大变化。其原理是 H_2S 气体在水中溶解度很低(25℃标准大气压下为0.34 g/(100 g))，溶液中的 H_2S 气体便由于过饱和而以气泡的形式存在于粪液中，这些气泡不断地积集、上升，在气-液界面受到压差等外界条件变化及人为干扰时便会破裂释放大量的 H_2S。这种气泡的产生具有不规则性和动态性。然而，气泡释放模型只用于解释 H_2S 从长期储放(如10 d以上)的液态畜粪，而本文所研究的保育舍每天清除猪粪尿，不存在长期储放的液态畜粪，所以舍内不规则的 H_2S 气体质量浓度变化有可能由其他未知的原因造成。

保育舍内 H_2S 质量浓度季节变化如图6b所示，所测 H_2S 质量浓度最高月平均值为(18.2 ± 1.4) μg/m³(2月份)，最高小时平均值为41.7 μg/m³(9月份)；最低月平均值为(8.2 ± 1.5) μg/m³(10月份)，最低小时平均值为0.9 μg/m³(12月份)。该研究结果也表明，冬季猪舍内 H_2S 质量浓度略高，其可能原因是一方面猪舍冲洗频次降低，舍内存储的粪污量较其他季节大，加上冬季采用地面加热系统，使得 H_2S 释放速率上升；另一方面，通风量的减小，也可能使得 H_2S 在舍内蓄积。

规模猪场环境的国家标准[19]要求保育舍 H_2S 的质量浓度控制在8 mg/m³以内。NI等[25]指出，在正常机械通风以及没有粪液搅拌的情况下，具有深坑式储粪池的猪舍内 H_2S 质量浓度一般低于1.5 mg/m³。人为搅拌粪便可使储粪池附近的 H_2S 浓度达到致死阈值[26]。所以从空气质量状况来看，本研究中的保育舍内 H_2S 浓度(年平均值为(8.2 ± 5.2) kg/m³)大大低于国家标准中规模猪场的最高浓度以及深坑式储粪池猪舍内的一般浓度。然而，养殖场所用水中的含硫量如果较高，会明显增加 H_2S 从粪水中的释放[27]，从而提高舍内的 H_2S 质量浓度。因此，其他地区保育猪舍即使采用同样的设计和管理，舍内 H_2S 质量浓度也有可能明显高于本研究得到的浓度。

2.5 猪舍 CH_4 质量浓度

由图7a的保育猪舍 CH_4 质量浓度小时平均值5日变化曲线显示，4月份、7月份及9月份平均质量浓度较低，均在3.6 mg/m³以下，但没有显示明显的昼夜变化规律。1月份的平均质量浓度最高值出现在18:00左右，随后逐渐下降，这有可能是粪污清理时间变化引起的。猪舍粪污清理主要是在07:00—09:00之间进行，CH_4 质量浓度在清理后降低，而在夜间不断上升，其主要原因是猪舍内的 CH_4 来自猪排泄物有机质降解产生，粪便自清理后不断累积形成部分厌氧状态，从而使产甲烷菌具有活性而分解有机质产生 CH_4。



(a) 小时平均值日变化　　(b) 季节变化

图7 保育猪舍 CH_4 质量浓度变化(以1号舍为例)

Fig. 7 CH_4 concentration variations in weaner house No. 1

保育舍内 CH_4 质量浓度季节变化如图7b所示，CH_4 质量浓度最高出现在冬季，其中12月份、1月份、2月份平均值分别为(4.8 ±2.9) mg/m³、(5.6 ± 0.4) mg/m³、(4.5 ± 1.1) mg/m³；较低值在春、秋季，分别为4月份的(1.8 ±0.6) mg/m³及10月份的(1.7 ±0.3) mg/m³。与 NH_3 夏季质量浓度最低不同，CH_4 浓度夏季较春秋季高，其主要原因可能是产甲烷菌活跃的适宜温度在30 ~65℃，夏季高温会促使舍内堆积的厌氧环境中粪便的分解产生 CH_4。

目前对规模猪场 CH_4 的质量浓度没有国家标准。国际上也未见到 CH_4 对畜禽健康影响的研究报道。而猪场引发的火灾主要是由储粪坑产生大量的泡沫造成[3]，泡沫中含有达到可燃体积分数(50% ~70%)的 CH_4。本研究结果表明，保育舍内 CH_4 浓度

(年平均值为(2.9 ± 1.9) mg/m^3)只有 CH_4 可燃体积分数的约十万分之一，而且与其它同类研究中得到的浓度也很接近：比如 DONG 等[28] 报道，北京一个猪分娩舍的 CH_4 年平均质量浓度为 6.6 mg/m^3。这些 CH_4 质量浓度未能显示对保育舍内的猪有任何潜在的环境危害。

3 结论

从 1 年连续性监测的华东地区典型保育猪舍内温湿度及主要污染气体质量浓度(CO_2、NH_3、H_2S 和 CH_4)的结果分析，得出以下结论：

(1)尽管保育猪舍采用了地暖管网和冷风机辅助以调节舍内温度，但全年的最低和最高小时平均温度仍分别达到 0.9℃ 和 42.0℃，超出了猪生长需求的最佳温度范围。全年的最低和最高小时平均相对湿度分别达到 31.1% 和 97.7%，也超出了国标的最低和最高临界值，不利于猪的健康生长。

(2)保育猪舍 CO_2 浓度白天高于夜间。白天小时平均最高质量浓度(3 534 mg/m^3)出现在 5 月份，已经超过国标规定的上限。在生产管理上需要对高 CO_2 质量浓度时段采取增加通风量等措施。

(3)保育猪舍 NH_3 质量浓度下午和傍晚高于上午，夏季高于其他季节。小时平均最大质量浓度达到 49.7 mg/m^3，是国标规定的 3 倍多，有待采取相应的措施。

(4)由于采用人工干清粪模式，保育猪舍内 H_2S 和 CH_4 的质量浓度很低，不致于对猪的健康生长以及猪舍的安全造成危害。

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