ATLANTIS PRESS

Advances in Engineering Research, volume 125

International Conference on Material Science, Energy and Environmental Engineering (MSEEE 2017)

Balance Model to Calculate the Ventilation Rate of a Mechanically Ventilated Finishing Pig House in East China

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Keywords: Pig production, Climate, Mechanical ventilation, Sensible heat, Moisture balance.

Abstract. This paper studies the ventilation rate of a mechanically ventilated finishing pig house with manure gutters from January 23th to 26th, 2016. The barn is located at the suburbs of Huainan, a city at north of Jiangsu in eastern China. Two methods for the calculation of the ventilation rate in pig building were compared based on the balances of animal heat and moisture for growing pigs. Data of temperature, relative humidity and air velocity was obtained in the interior of building, as well as the external conditions. The operational status and rotational speed of ventilation fans were monitored at six stages. The analysis shows that temperature of all units in pig house ranged from11.5 ℃ to 14.7 ℃ about 30min in average, and relative humidity from 44.9% to 82.6%. The average air temperature inside the pig house was 13.7 ℃, while the relative humidity was 69.7%. The inside air temperature was increased by 17.8 ℃ and relative humidity reduced by 6.8% in average than outside. The average air velocity in the lower area of the building was 0.28 m/s. The average inlet and outlet air velocity of the pig building were 3.2 and 5.3 m s^{-1}, respectively. The directly measured ventilation rate of a pig barn was 6069 m^3 h^{-1}. The average moisture and heat balance ventilation rate of pig barn was 6207m^3 h^{-1}, 5880 m^3 h^{-1}, and the difference of ventilation rate between directly measured and balance measured during the field experiment was 137 m^3 h^{-1}, 189 m^3 h^{-1} respectively.

1. Introduction

Air emissions from livestock production can be categorized broadly into GHG emissions and all other air-pollutant emissions, such as ammonia (NH_3), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) [1]. Livestock and their waste are major source of gaseous emissions, as well as affect soil and water quality. Ammonia is an atmospheric pollutant and responsible for eutrophication and soil acidification, while CO_2, CH_4 and N_2O are greenhouse gases (GHG) that contribute to global warming [2]. Quantification of gaseous emissions requires determination of the concentration of the air contaminant and the ventilation rate of the emitting source. One key issue is to estimate the ventilation rate and then to quantify the gaseous emissions [3]. In confined swine house, ventilation is critical to ensure comfortable indoor environment for animal production. Several article proved that appropriate ventilation can also improve air quality inside pig buildings [4]. However, measuring ventilation rates in commercial animal houses is difficult in practice [5].

A number of primary techniques exist for determining ventilation rate of livestock buildings, including: anemometers, tracer gas, heat and moisture balance method. An approach applicator to mechanically ventilated buildings is to measure the air velocities of the exhaust fans under specific static pressure and monitoring of number of operating fans [6]. Hot wire and three dimensional ultrasonic wind anemometers can be used to measure the air velocity in a ventilation opening [7, 8]. A new technique, known as the Fan Assessment Numeration System (FANS), was introduced for continuously monitoring exhaust fan to improve in situ measurement accuracy of fan airflow capacity

[9]. However, continuously monitoring or regularly checking airflow of ventilation fans can be a daunting task, especially in barns with numerous fans [10].

Tracer gas techniques have become widely used to measure the ventilation rates in buildings indirectly and showed reliable results. The basic principle of the method is the conservation of mass in the ventilation process: by monitoring the injection and concentration of the tracer, the exchange of air in the building can be determined [7]. The tracer gas method can be applied in three different ways, including: tracer gas decay, constant concentration and constant injection rate method. Tracer gases used in the literature including nitrous oxide (N_2O) [11], carbon monoxide (CO) [12], carbon dioxide (CO_2) [6], sculpture hexafluoride (SF_6) [13], and krypton (^{85}Kr) [14]. The CO_2 mass balance method has been applied to determine the ventilation rate from both mechanically and from naturally ventilated [15] livestock buildings. However, applications of tracer gases in production facilities are often limited because the process requires uniform air - tracer mixing to ensure good results, which is difficult to achieve in commercial production settings. Van Buggenhout et al [16] demonstrated that in a mechanically ventilated test installation with accurate reference method, tracer gas experiments were performed to demonstrate the apparent difficulties. Certain tracer gases, such as SF_6, also cause negative impacts to the environment.

Blames and Pedersen [17] described some steady-state balance methods for ventilation rate measurements of pig building, including heat balance and moisture balance. Then measurements of outdoor and indoor temperature and relative humidity were made, it was possible to calculate the ventilation rate based on the heat and moisture balances of the building [18]. These methods largely depend on the animal production of sensible heat and latent heat. Sameer [1-3] investigated factors that influence moisture and heat production include flooring system, stocking, density, watering, and moisture content of the forages, animal activity and relative humidity. Sensitivity analysis showed that the estimations were more precise in cold than in warm periods, and it was concluded that heat and moisture balances were not applicable for calculations of ventilation rate in uninsulated buildings [17]. The heat and moisture balance showed reliable results through winter seasons and acceptable results to some extent through summer seasons [1]. The objective of this paper was to compare moisture and sensible heat based balance methods for the estimation of ventilation rates in a mechanically ventilated pig house based on 30 min values with wall fan outlet and sidewall inlets.

2. Materials and methods

2.1 Description of the pig building

This study is based on measurements recorded at an experimental pig building located at the suburbs of Huainan, a city at north of Jiangsu in East China (33°30′57.81” N, 118°49′23.54 E”, 17m amsl; coordinates refer to the building’s location). Field experiments were carried out during the cold season. The mechanically ventilated pig barn with manure water flushing systems, as shown in Figure 1, has dimensions of 54.0 × 14 × 3.6 m (L × W × H) and a capacity of 500 pigs. The pig barn was divided to 2 sections (54.0 × 7.0 m) arranged on the south-north orientation with partition wall. Every section approximately 250 animals were hosted in 7 pig pen. Each pen contained one feeder and one drinker and occupied by a total of 36 animals. New pigs were sent into the barns at about 20 kg and were marketed at about 110 kg. The growth cycles were 4 to 5 months long.

The barn had air inlets on both north and south sidewalls. Each air inlet had dimensions of 55.0 × 25.0 cm (W × H), with 1.8 m height from the floor. There were three ventilation fans in the west wall of each sections of pig barn. One continuous 92-cm diameter-belted variable speed fan was located in the center of the two fans. Two fans were 130-cm diameter-belted exhaust fans. During colder weather, the sidewall air inlet was open, allowing uniform fresh air to enter the barns. Each barn had two hydronic methods to keep the barn warm when the indoor temperature was too low in cold weather. In warm weather, the barns were always under tunnel-ventilated conditions, and two 1.30-m exhaust fans normal operation. Manure storage was collected in gutters along the length of the barns from east to west, and flowed into outside storage cesspool.

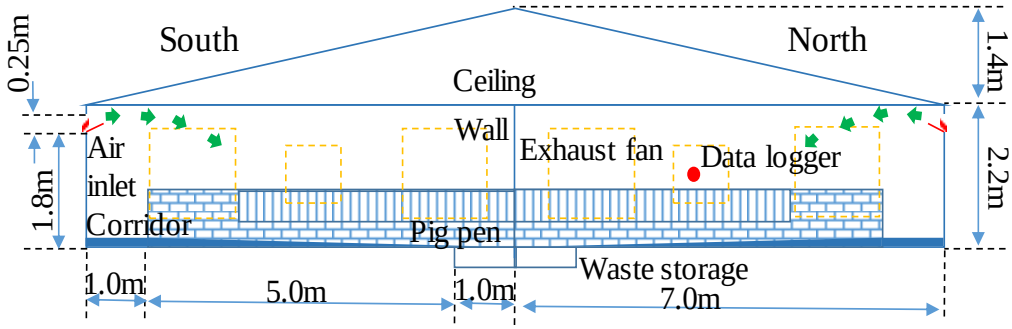

Fig. 1. Pig barn dimensions and positions of ventilation openings.

2.2 Data acquisition procedures

The field experiment was conducted as the first step to determine the main environmental problems in the commercial pig house during the cold season. Air temperature, humidity, ventilation rate, and wall surface temperature were measured during three days (January 23th and 26th, 2016) with stable weather conditions to obtain reliable data.

To monitor the thermal environment, the three sensors were installed in the building at 1.0 m height, across the length of the building in the central axis distributed 13.5 m apart from each other. Outdoor air temperature and relative humidity were monitored with a sensor placed 10 m away from the barn, and protected in a plastic shield with lateral slots in order to be protected from water and indoor dust. The air temperatures and relative humidity inside and outside the pig building were measured using an HOBO Data Logger (HOBO U23-001, Corporation, Pocasset, MA, USA) with accuracy of ±0.21 ℃ and ±2.5%, respectively. A noncontact infrared thermometer (Fluke 572-2, Fluke, WA, USA) was used to measure the surface temperatures of each wall during the experimental period with the emissivity values of 0.95, 0.8, 0.85 and 0.90 for concrete, iron materials, glass and pig, respectively.

The air velocities at each inlet and outlet were measured using digital anemometers (TM826, TECMAN, HK, China) and the averaged air velocity was used to calculate the ventilation rates. Exhaust fan capacity was monitored at the beginning and end of the experiment. Air velocity data was collected during day and night periods at three different points across the length of the building in the central axis at 1.0 m of height.

2.3 Mathematical model

The ventilation rate throughout the building can be determined by calculating the mass balance of H_2O flow. The calculations of moisture balance were based on Blames, Pedersen and Schauberger [17, 18, and 19]. The following mathematical model describes the moisture balance:

$$V_{moist} = \frac{3600AL}{h_{vap}(H_i - H_o)} \tag{1}$$

Where, V_{omits} ($m^3\ h^{-1}$) represents the ventilation rate subject to the moisture balance, L (W) is the latent heat production [Eons (3)], H_i (%) is the relative humidity inside the building and H_o (%) is the relative humidity outside the building.

h_{ap} ($J\ kg^{-1}$) is the heat of vaporization of water, that can be obtained, according to the indoor temperature T_i (℃) from the expression: $(2501\text{-}2.42\ T_i)\times10^3$. On the other hand, A represents the relative animal activity according to the different animal actions during every 24-h period, and can be calculated as follows equations [Eons (2)]:

$$\mathrm{A} = 1 - a\sin\left(\frac{2\pi}{24}(h + 6 - h_{min})\right) - b\sin\left(\frac{2\pi}{c}(h - d)\right) \tag{2}$$

Where, $h$is time of day (24 hour clock), and h_{min}=1, a=0.31, b=0.15, c=6.0 and d=11.4 are constants.

$$\mathrm{L} = \Phi_{tot}^{*} - S \tag{3}$$

Where, Φ^*_{tot} (W) represents the total heat production at temperatures different from 20 ℃, and S (W) is the sensible heat production at house level, can be calculated as follows equations [Eqns (4) and (5)]:

$$\Phi^*_{tot} = N[\Phi_{tot} + 0.012\Phi_{tot}(20 - T_i)] \quad (4)$$

Where, Φ_{tot} (W) represents the total heat production for fattening pigs at 20 ℃, and N represents the number of pigs housed in the building.

$$S = K_S\left(0.62\Phi^*_{tot} - 1.15 \times 10^{-7}T_i^6\right) \quad (5)$$

Where, K_s represent a correction factor for the sensible heat production at house level. Φ_{tot} (W) can be calculated as follows equations [Eons (6)], Where m (kg) represents the live mass.

$$\Phi_{tot} = 5.09m^{0.75} + [1 - (0.47 + 0.003m)][n \times 5.09m^{0.75} - 5.09m^{0.75}] \quad (6)$$

The heat balance equation for the sensible heat can be written as (Blames et al, 2005):

$$V_{heat} = \frac{3600(AS - S_{trans})}{h_{sp}\rho(T_i - T_O)} \quad (7)$$

Where, H_{eat} (m^3 h^{-1}) is the ventilation flow from the sensible heat balance, h_{asp} (J kg^{-1} ·$℃^{-1}$) is the specific heat of air, ρ (kg m^{-3}) is the air density, T_o (℃) is the outdoor temperature of air, S_{trains} (W) is the transfer of sensible heat through the building, can be calculated as follows equations [Eons (8)]:

$$S_{trans} = \sum_{j}^{n} U_j A_j (T_i - T_O) \quad (8)$$

Where, U_p (W m^3 ·$℃^{-1}$) is the thermal transmission coefficient, A_{ja} (m^2) is the area of all these elements. Data values were analyzed statistically using the statistical package SAS 9.2 (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1 Climate conditions

Descriptive statistics for environmental indicators in pig building are presented in Table 1. The range of surface temperature for pig building was wide, with wall temperature ranging from 7.6 to 14 ℃, then ceiling and floor temperature was 15.3, 21.2 ℃, respectively. The average air temperature inside the pig house was 13.7 ℃, while the relative humidity was 69.7%. On the other hand, the average outdoor air temperature was -4.6 ℃, and the average relative humidity was 65.2%.

The inlet air was slightly warmed near the ceiling and moved downwards to both sides of the walls of the pens. Due to the minimum ventilation by the air fan attached to one side of the wall, the average air velocity in the lower area of the building was 0.28 m/s. The average inlet and outlet air velocity of the pig building were 3.2 and 5.3 m s^{-1}, respectively.

Table 1, Environmental indicators in pig building

Class	Location	Value
Surface temperature/ ℃	Wall	East: 7.6 West: 14.0 South: 13.7 North: 8.8
	Ceiling	15.3
	Floor	21.2
Air temperature/ ℃	Indoor	13.7
	Outdoor	-4.6
Air humidity/ kg m^{-3}	Indoor	0.00832
	Outdoor	0.00239
Air velocity/ m s^{-1}		0.28
Inlet air velocity/ m s^{-1}		3.2 (2.5 ~ 3.8)
Outlet air velocity/ m s^{-1}		5.3 (4.5 ~ 6.1)

Fig. 2a shows the air temperature inside and outside of the pig house in different measuring points during the field experiment between 00:00 and 23:00 when air temperatures of inside pig house were

relatively stable without sudden drop due to door opening for internal managements. On the other hand, the outside temperature reached its maximum 1.3 ℃ at 12:30 and then decreased to its minimum -8.2 ℃ at 22:30. The analysis shows that indoor average half hour temperature across all units ranged from 11.5 ℃ to 14.7 ℃. The difference between indoor and outdoor temperature during the experiment ranged between 11.0 ℃ and 21.7 ℃, while its mean value equaled to17.8 ℃. It is clear that temperature levels during inside were higher than the outside ($P < 0.05$).

Relative humidity levels inside and outside the pig building are presented in Fig. 2b, when data from three measuring points were available. During the field experiment relative humidity inside the pig house varied between 44.9% and 82.6%, and the relative humidity outdoor varied between 41.6% and 80.3%. The difference between indoor and outdoor relative humidity during the experiment ranged between 0% and 22.4%, while its mean value equaled to 6.8%. Significant differences were detected between indoor and outdoor relative humidity levels ($P<0.05$). Pedersen [17] investigated a useable prediction of the ventilation rate was possible on a 24h basis when the inside to outside differences of air temperature and absolute humidity were larger than 2 ℃ , 0.5 g m^{-3} , respectively.

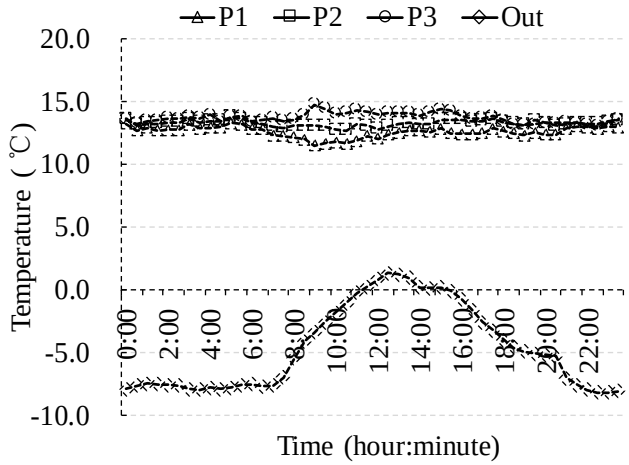

Fig. 2a Temperature

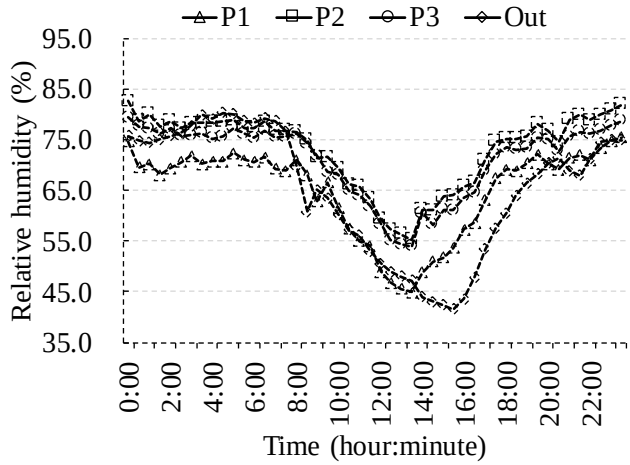

Fig. 2b Relative humidity

Fig. 2 Measured outdoor and indoor air temperatures and relative humidity

3.2 Ventilation rate

Ventilation rate are very important considerations in a pig house ventilation system. Three methods for the calculation of the ventilation rate in east China pig house with mechanical ventilation were compared on the basis of the balances of animal sensible heat, moisture balance and direct measurement. Fig. 3 shows the ventilation rate over 30m minutes based on the three methods. Tables 2 show the average ventilation rate in pig house through six stage, according to the different measurement methods, which are: moisture balance, sensible heat balance and direct measurement.

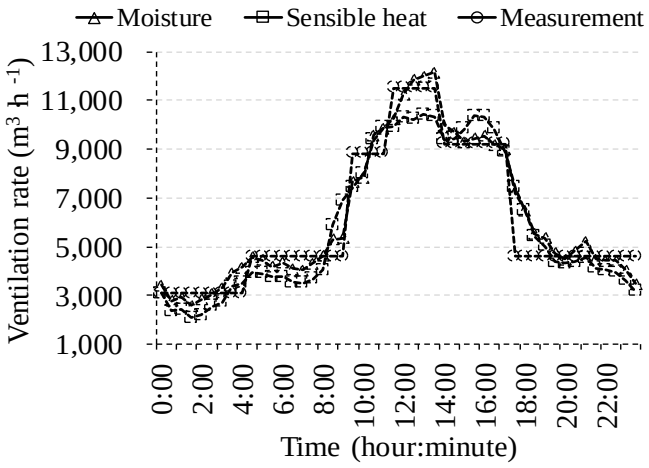

Fig. 3 Diurnal variation of ventilation rate for pig building based on sensible heat, moisture balance and direct measurement

The three methods determined ventilation rates showed the same pattern in following the outside temperature profile. The directly measured ventilation rate of a pig barn ranged from 3100 m^3 h^{-1} to 11520m^3 h^{-1} with an average of 6069 m^3 h^{-1}. The moisture balance measured ventilation rate varied from 3231 m^3 h^{-1} to 11498m^3 h^{-1} and the heat balance measured ventilation rate changed between 2705m^3 h^{-1} and 10242m^3 h^{-1} (Table 2). The operational status and rotational speed of ventilation fans were monitored at six stages. The minimum and maximum ventilation rates occurred in 00:00-5:00 and 11:00-14:00, respectively. The average moisture and heat balance ventilation rate of pig barn was 6207m^3 h^{-1}, 5880 m^3 h^{-1}, and the difference of ventilation rate between directly measured and balance measured during the field experiment was 137 m^3 h^{-1}, 189 m^3 h^{-1}, respectively. However, small differentiations existed between the three methods, presumably resulting from the dynamic nature of the environmental conditions and pigs activities.

Table 2, Ventilation rate for pig building in different stage

Time	Moisture balance	Sensible heat balance	Direct measurement
0:00-5:00	3231±531	2705±511	3100±NA
5:00-9:00	4540±544	4387±1348	4608±NA
9:00-11:00	8750±1130	8677±1156	8832±NA
11:00-14:00	11498±776	10242±186	11520±NA
14:00-17:00	9456±330	9732±531	9216±NA
17:00-0:00	4983±1001	4685±1170	4608±NA

4. Conclusion

The directly measured ventilation rate of a pig barn was 6069 m^3 h^{-1}. The average moisture and heat balance ventilation rate of pig barn was 6207m^3 h^{-1}, 5880 m^3 h^{-1}, and the difference of ventilation rate between directly measured and balance measured during the field experiment was 137 m^3 h^{-1}, 189 m^3 h^{-1}. For mechanical-ventilated growing pig house using manure gutters with daily manure removal, balance based on pig metabolic rate can be used to determine house ventilation rate with good result.

Acknowledgements

Funding was provided by Jiangsu Agriculture Science and Technology Innovation Fund (JASTIF) [CX (14)5074], Science and Technology Agency of Jiangsu Province (BE2014342-1) and Natural Science Foundation of Jiangsu Province (BK20170614). We sincerely appreciate the cooperation and assistance of the pig producer in the implementation of this field study. The authors would like to thank all farmers who participated in this study.

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