Simple Odour Release Model for Swine Finishing Houses

G. Schauberger[*], A. J. Heber, T.T. Lim, J.-Q. Ni, D.S. Bundy, B.L. Haymore, C.A. Diehl, and R.K. Duggirala

ABSTRACT

Odour emission rates from four, identical, 1,000-head, mechanically-ventilated swine finishing houses between April and August 1997 were analyzed. Each building had long-term manure storage beneath a fully slatted floor, two sidewall curtains, a curtain on the west end wall, four pit ventilation fans, and five exhaust fans on the east end wall. Odour was determined using olfactometry with four to six trained panelists. The median of the specific odour emission from the four buildings was 75 OU/s per 500 kg pig live mass ($P<0.05$) based on 112 simultaneous odour and ventilation rate measurements. Odour emission was modeled with an exponential function to describe the influence of the indoor air temperature and a power function to describe the influence of the ventilation airflow rate.

Keywords: Ammonia, hydrogen sulfide, temperature, ventilation, airflow, air quality

INTRODUCTION

Public concern over air pollution from swine production and stricter environmental regulations have created a great need for odour-related research in the swine industry (Thu, 2002). Apart from empirical guidelines for estimating a reasonable separation distance, it can also be calculated by atmospheric dispersion models. For odour sources, the required inputs for such a model include: odour emission rate; volumetric airflow rate of the source (ventilation rate of the building ventilation system), area and height of the ventilation exhaust, and exhaust air temperature. Until now, very basic odour emission patterns are considered in atmospheric dispersion models and setback guidelines.

However, there is a lack of baseline odour emission data for swine housing (Lim et al., 2001). Therefore, the objective of this paper was to analyze field data collected at commercial swine finishing buildings and to develop an empirical odour emission model.

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MATERIALS AND METHODS

Model Description

For some parameters such as indoor air temperature, indoor air velocities, and physical activity of the animals, there is isolated evidence by various authors that they have an influence on building odour release. A model was developed that is based on the concept that odour production is caused by several sources like slurry, feed, and the animal itself. These animal-related factors are represented by the individual live mass of the animals. Additionally, the variable E was introduced that describes the modification of odour release R based on various factors. $E = P\,R$ where E is emission rate (OU/s), P is odour production rate (OU/s), and R is an odour release modification factor.

The production term P is given by $P=C_P\,M_{tot}$ where C_P is a constant, OU s^{-1} kg^{-a}, estimated by the model, $M_{tot} = N\,M^a$, the modified total live mass of the animals, kg^a, N is the number of animals, and M is live mass of the animals, kg. The model is based on either M (a=1), the metabolic live mass (a = 0.65 to 0.75), or the number of animals independent of their mass (a=0).

The modification factor R is a dimensionless function based on various parameters that influence odour release. The influence of each parameter on odour emission can be expressed more specifically with rescaled functions than with original parameters. The odour release modification R is expressed by a product of these functions $R = C_T F_T\, C_v F_v\, C_A F_A$ using F_T to rescale the influences of the indoor temperature T of the livestock building, F_v, a function giving the air velocity v close to the polluted surfaces and the animals; and F_A the diurnal variation of the physical animal activity A. C_T, C_v, and C_A are the coefficients of the regression.

The rescale function of the indoor temperature T is given by an exponential relationship $F_T = \exp\,[c_T\,(T-T_0)]$ where c_T is a constant; T is indoor temperature (°C), and T_0 is a reference temperature of 15°C.

The rescale function of air velocity v close to the slatted floor and in the animal space was parameterized by the ventilation rate of the livestock building using the power function $F_v = (V_n-1)^b$ where the ventilation rate, $V_n=V / N_d\,V_d$, is normalized to the design number of animal places in the building, N_d, and the design minimum ventilation rate of the building, V_d. The analyses was conducted with assumptions of $N_d = 1000$, and a minimum ventilation rate for growing pigs of $V_d = 3.31\ 10^{-3}$ m³ s^{-1} per pig (MWPS, 1990).

The diurnal variation of the animal activity is an important factor that modifies odour release. The diurnal patterns can be described by a sinusoidal function with i-th harmonics $F_A = 1 + \Sigma\, c_{A,j} \sin (2\,\pi\, i\, (t+\varphi_i)\ /\ \tau))$ where $c_{A,i}$ is the amplitude, τ is the duration of the period, t is the time of the day and φ_i is the time lag.

Measurements

Odour emission measurements were conducted in four, identical 1000-head, mechanically ventilated, grow-finish buildings (buildings A, B, C and D). Each of the buildings had a 2.4 m deep pit under a fully slatted floor with a pit surface area of 799 m^2. Detailed drawings of these buildings are presented by Heber et al. (2001).

Odour emission samples were collected in 80-L Tedlar® bags and sent overnight to Iowa State University, Ames, Iowa, for analysis by dynamic dilution olfactometry. The dynamic olfactometer presented mixtures of odourous air samples and filtered, odour-free air at known dilutions at controlled airflow rates. Odour emission (OU/s) in this paper is expressed as the product of the odour concentration in OU/m^3 and the building ventilation rate in m^3/s. A "measurement" of odour in the building consisted of the average concentration of one to four sample replications depending on the air sampling protocol and number of good samples.

A detailed description of the measurements can be found in Heber et al. (2001).

RESULTS

Descriptive Statistics

In a descriptive statistic of the measurements, the data space that is covered by the measurements can be seen in table 1. To describe the distribution of the parameters, the percentiles were used because they are independent from the distribution, whereas for the use of mean and standard deviation, a normal distribution had to be assumed. The specific odour emission behaved like a log-normal distribution (Fig. 1).

The specific odor emission exhibited a log-normal distribution, fig. 3. The covariance between the different parameters is shown in table 2 using the Pearson regression coefficient r.

The strong relationship between the T and V (Fig. 2) is used to divide the entire data set into three subsets. To investigate the influence of the indoor temperature T by eliminating the influence of the ventilation rate V as cofounder, two sub-sets were used. The subset V-LOW was characterized by a low ventilation rate (<13.89 m^3/s) and the subset V-HIGH had a ventilation rate greater than 55.6 m^3/s. The influence of ventilation rate on odour emission was investigated with the third subset (T-CONST) that included all T between 21°C and 25°C. The third subset is characterized by low variability of indoor temperature and the full range of ventilation rate V.

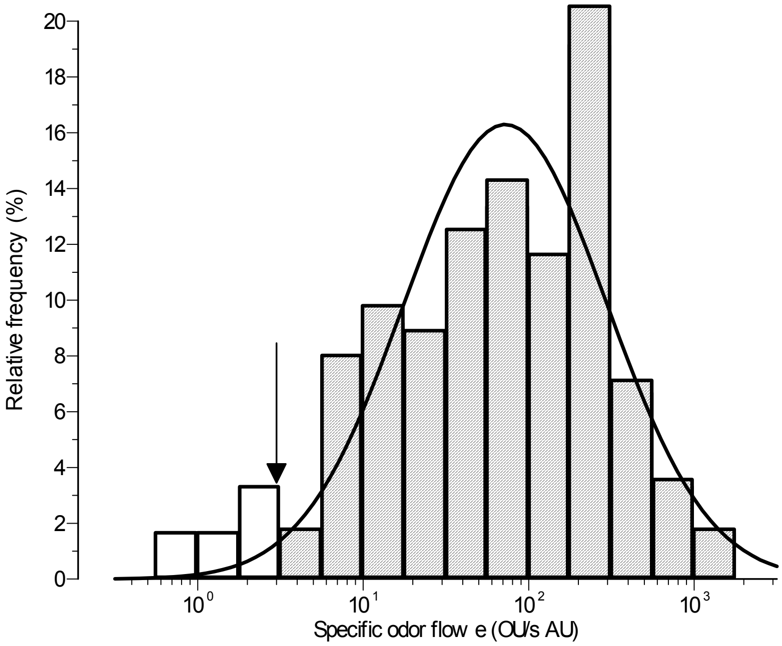

Fig. 1: Relative frequency distribution of the measured specific odour emission e in OU/s-AU of the four buildings and a log-normal distribution with a mean of 1.86 and a standard deviation of 0.61. The arrow marks the cut-off values of outliers, which were eliminated for subsequent data analyses (empty bars)

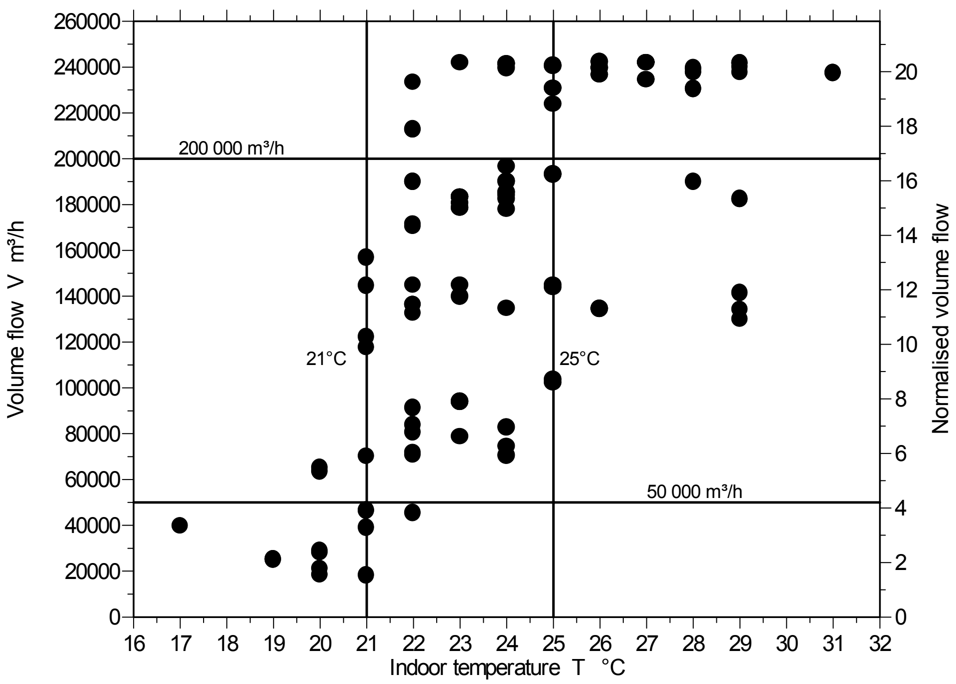

Fig. 2: Scatter diagram of ventilation airflow and indoor temperature. The lines show the limits for dividing the overall data set into three subsets to eliminate influence of confounders. On the right y axes, the ventilation rate V_n is normalized by product of the number of animals (N_d=1000) with the minimum ventilation rate per animal for winter time (V_d=3.31 10^{-3} m³/s)

Table 1. Basic statistics of measured values for entire data set and for individual buildings. (V volume flow, T indoor temperature, M_{tot} total live mass, C_O odour concentration, e_O specific odour emission, C_N NH_3 concentration, e_N specific NH_3 emission, C_S H_2S concentration, e_S specific H_2S emission)

	V	T	M_{tot}	C_O	e_O	C_N	e_N	C_S	e_S
	m³/s	°C	AU	OU/m³	OU/s-AU	mg/m³	ng/s-AU	ng/m³	ng/s-AU
Maximum	67	31.0	203	2904	1653	12.9	3483	1069	290
95th-P	67	29.0	187	1220	635	7.9	2763	493	220
75th-P	66	26.2	153	512	226	2.4	1477	186	108
Median	51	24.1	118	215	74.9	2.0	974	95	46
25th-P	29	22.1	92	91	25.2	1.0	183	24	4.6
5th-P	8	20.3	41	15	7.0	0.28	123	4.9	1.7
Minimum	5	17.4	22	12	3.3	0.16	58	3.6	0.7
n	112	112	112	112	112	108	108	108	108
CI ul	53	24.7	130	269	129	1.6	1174	123	58
CI ll	40	23.0	106	181	52.8	2.1	530	78	38
Median									
A	51	24.7	106	215	87.1	2.0	974	123	59
B	51	24.4	94	198	92.5	2.0	1379	88	46
C	33	22.6	146	198	59.4	1.4	183	34	8.5
D	59	22.3	165	181	57.2	0.8	165	18	4.0

P percentile, n number of cases, CI confidence interval, ul upper limit, ll lower limit,

Table 2: Correlation coefficients between measured parameters (n=108). (V volume flow, T indoor temperature, M_{tot} total live mass, C_O odour concentration, e_O specific odour emission, C_N NH_3 concentration, e_N specific NH_3 emission, C_S H_2S concentration, e_S specific H_2S emission)

	V	T	M_{tot}	C_O	e_O	C_N	e_N	C_S
T	0.69[a]	1						
M_{tot}	-0.18	-0.63[c]	1					
C_O	-0.04	-0.11	0.10	1				
e_O	0.30[b]	0.31[b]	-0.23[a]	0.79[c]	1			
C_N	-0.58[b]	-0.33[c]	0.01	0.27	-0.06	1		
e_N	0.28[b]	0.68[c]	-0.82[c]	0.01	0.33[c]	0.11	1	
C_S	-0.46[c]	-0.19[a]	-0.16	0.30[b]	-0.03	0.81[c]	0.23[a]	1
e_S	0.16	0.64[c]	-0.81[c]	-0.05	0.18	0.07	0.86[c]	0.34[c]

[a]P<0.05; [b]P<0.01 [c]P<0.001

Model Development

The exponent a, which describes the influence of live mass of pigs on odour production was preselected as a=1. This was necessary because of the cross-correlation of M with T. The first parameter investigated was T. By using an exponential function, a regression analyses was performed with the subset V-LOWV and V-HIGH. Both subsets have sample sizes of 15 and 39, respectively. The temperature ranges were 17.4°C to 22.0°C for V-LOW and 25.4°C to 31.0°C for V-HIGH. Both data-sets showed a weak increase of odour emission with indoor temperature but only the results of the V-HIGH sub-set were statistically significant (P<0.05). The coefficient c_T was determined to be 0.127 with a standard deviation of 0.015 (P<0.001).

The influence of the ventilation rate on the odour emission was established with the third data-set. The regression analysis of the specific odour emission e with the normalized ventilation rate V_n resulted in an exponent b of 1.029 with a standard deviation of 0.298. The regression was statistically significant (P<0.001) (r^2 = 16.4%).

The diurnal variation could not be determined from the data set because of the limited variability in odour sample times, which were between 8:50 and 17:52. Therefore, it was decided to use the parameters for a mono-sinusoidal function (i=1) with only one harmonic with an amplitude $c_{A,1}$=0.40 and a time lag φ_1= -7.25 h. The minimum animal activity of fattening pigs occurs around 01:15 at night (Pedersen, 1996; Pedersen and Takai, 1997).

Using the three rescale functions instead of indoor temperature T, ventilation rate V, and the activity of the animals A, the specific odour emission e_O can be expressed with the following combination of these functions: $e_O = C_P(C_T F_T \ C_v F_v \ C_A F_A)$. The result of the step-wise regression is shown in table 3. The error term and the F value are presented with the calculated regression coefficients for the three rescaled parameters. The F value compares the variance without a model with the variance of the selected model.

Table 3: Results of the stepwise regression analyses of the specific odour emission e_O and the rescaled parameter F_T, F_v, and F_A. The cross denotes which parameter was fitted by the regression

Rescaled parameter			Regression coefficient (± std. error)	F value
Temperature F_T	Air velocity F_v	Activity F_A		
+	$C_F F_F$=1	$C_A F_A$=1	$C_P C_T = 49.8 \pm 6.0$	10.21 (p<0.002)
$C_T F_T$=1	+	$C_A F_A$=1	$C_P C_V = 12.1 \pm 1.4$	10.81 (p<0.002)
+	+	$C_A F_A$=1	$C_P C_T C_V = 2.87 \pm 0.35$	9.96 (p<0.003)
+	+	+	$C_P C_T C_V C_A = 2.12 \pm 0.26$	10.08 (p<0.002)

The results show that air velocity, which was parameterized by ventilation rate, gave the highest F value in the regression analyses. The model performance was not improved by adding other predictors (temperature and/or activity). Nevertheless, the F value was nearly the same for all four model variants. Each addition of other parameters reduced the F value and therefore model performance.

DISCUSSION

The odour emission data presented in this paper were part of a comprehensive data set that included other air emissions and parameters describing the hygro-thermal situation of the animals. To give a concluding picture of the barn air emissions we included ammonia and hydrogen sulfide, which are released from the same sources inside the barn. Further, they are known as cofounders for odour, nevertheless they cannot be used as guiding substances to substitute for odour measurements because of their weak correlations to odour.

The odour emission of swine finishing buildings depends on various parameters. The main factors that were determined to be relevant were the live mass of the livestock, the indoor air temperature, the air velocity across inside surfaces of the building, and the diurnal variation of animal activity. The data set was used to calculate the coefficients of the model.

The univariate analyses of emission data (e.g., odour emission as a function of temperature) does not take into account confounding factors. An obvious example is the strong correlation between indoor temperature and ventilation rate. The influence of the second parameter cannot be eliminated in a univariate analyses. Therefore an overestimation can be expected in same cases (e.g. increasing indoor temperature is associated with with increasing ventilation rate). This has to be taken into account by the analysis of Jeppsson (2002) and Ogink and Koerkamp (2001). If a reciprocal behavior between parameters can be expected, then an effect can be weakened or totally disappear. In our analyses of the correlation coefficients (table1), this could be observed for the indoor temperature and the concentration of odour, ammonia and hydrogen sulfide, where the dilution of the ventilation rate compensates for the increased release caused by temperature.

The influences of selected parameters were isolated by dividing the data set into subsets. These subsets were used to fit the rescale functions so the influence of the original parameters could be considered in a more specific way. Therefore we were able to analyze the odour emission bivariately.

The differences between the effect of the ventilation rate on H_2S on one side and ammonia and odour on the other side could have caused differences of the release. Ammonia and odour are predominantly released by the animals and fresh manure on the slatted floor. In this area the ventilation rate is directly affecting the air velocity. Hydrogen sulfide is released predominantly by the manure inside the pit. There, the air velocity is only weakly related to the ventilation rate due to the aerodynamic resistance of the slatted floor.

The relevance of the live mass of the animals can be shown by the use of the live mass specific odour emission instead of the building odour emission to characterize the emission. The specific odour emission e is related to the live mass given in AU (1 AU=500 kg).

The review concerning the odour emission of livestock buildings by Martinec et al. (1998) showed a wide range of published data describing odour release. For example, the live mass specific odour emission for fattening pigs varied between 38 and 495 OU s^{-1} AU^{-1} for fully slatted floors and between 8 and 134 OU s^{-1} AU^{-1} for bedded floors. The main factors affecting the reported variation (Martinec et al., 1998) were the various methods of husbandry and the influence of overall building management.

The introduction of the modified live mass of animals by M^a is based on the assumption that other exponents besides a=1 could be used. For example, the total energy and CO_2 release is proportional to metabolic mass with an exponent a between 0.65 and 0.75 (CIGR, 1984). Ogink and Groot Koerkamp (2001) used odour emission (OU/s) per animal. This could be interpreted that the emission is independent from the live mass, which means that the exponent is zero. On the other hand, Ni (1998) found an exponent of a=1.43 to describe manure production as a function of live mass.

By the cross correlation of live mass with indoor air temperature, it was not possible to fit the exponent by the data-set. Therefore, a value of a=1 was used, which is widely reported in the literature.

The selected exponential function to describe the increase of odour release with increasing indoor temperature is based on that used by Ni (1998) and Jeppsson (2002) for ammonia. If the exponent of c_T=0.127 from this study is compared with other studies, it has to be considered that an attempt was made to reduce the effect of other parameters (increasing ventilation rate with temperature) by grouping the data. The weak correlation that was found for indoor temperature could be based on the interaction of temperature with total live mass of the livestock (table 2). Therefore, the influence of temperature on odour release could not be handled independently. The total live mass has to be seen as a confounding factor, influencing this relationship.

The air velocity at the surface where odour is released is a major factor influencing the transfer coefficient. In a detailed review for ammonia release, Ni (1999) showed the importance of the convective mass transfer. The influence of air velocity above the surface where odour is released can be parameterized by the ventilation rate using a power function. The exponent lies between 0.8 and 0.7. For a naturally ventilated barn with deep litter, Jeppsson (2002) found an exponent of 0.69 which is far less than what we found for the mechanically ventilated building with a fully slatted floor. The differences in the design could be the reason for the stronger influence of the ventilation rate in the barn we measured.

Total energy, methane, CO_2 and ammonia release by livestock buildings typically show a typical diurnal variation (Pedersen and Takai, 1997; Schauberger and Pilati, 1998, van Ouwerkerk and Pedersen, 1993; Jeppsson, 2002; Ni et al., 2002), strongly correlated to animal activity. Ammonia concentration shows a distinct day/night fluctuation. For eight different sow houses, the ratio of the mean ammonia concentration between day and night was about 1.28, for the daily extremes 2.10 (Phillips et al., 1998). Jeppsson (2002) found a diurnal fluctuation around the daily mean with values between 6% and 247% for ammonia.

To develop a model, a data-set should cover the entire range of parameters that are used as input parameters for the model. In this respect the data set shows some weak points. Firstly, the data set was mainly gathered in the warm season between April and August. Therefore, only few data are available for low indoor temperature and low ventilation rate of the ventilation system (Fig. 2). Secondly, odour samples were only taken during daytime. Therefore, the influence of diurnal variation of animal activity on odour emission could not be confirmed by the measurements.

A data set with enough samples to fit the proposed odour model with greater accuracy is needed to increase its reliability. Measurements over complete fattening periods during different seasons with day and night samples are needed.

CONCLUSIONS

- Swine finishing buildings with deep pits emitted about 75 OU/s per AU.
- Odour emission increases with inside temperature according to an exponential function.
- Odour emission increases with building ventilation rate according to a power function.

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