Model to predict human and pig exposure to gaseous contaminants emitted from stored manure

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This paper describes a model for quantifying human and pig exposure to gaseous contaminants as a result of mass transfer from stored manure to ventilation air in a confinement unit. A lumped-parameter model is used to simulate 24-hr average concentration profiles within the pig unit. Mass transfers from manure pit to air are derived from the two-film resistance theory. A preliminary data base for a typical pig unit is used to calculate a range of air concentrations and pig exposures for three growth stages: growing, nursery, and prenursery. The model is used to estimate exposure dose factors for four gaseous contaminants: methane, ammonia, hydrogen sulfide, and carbon dioxide. The calculated ratio of ventilation air exposure to concentrations in stored pig manure is compared to measured values from literature researches to adjust the transfer coefficients in order to estimate pig exposure in terms of a lifetime inhalation dose factor. A sensitivity analysis for identifying the important parameters in the simulation model is also presented.

Keywords: exposure, gaseous contaminants, mass transfer, stored swine manure, inhalation dose factor

1. Introduction

Workers and pigs in pig units are exposed to a wide range of airborne contaminants that cause respiratory irritation and sensitization. Longitudinal hygiene studies[1] indicate that many factors influence the presence and concentrations of contaminants in the air, but it is clear that a large proportion of exposed pigs and farmers may suffer respiratory symptoms.

Epidemiological studies in the United States, Denmark, and Canada have all demonstrated a greater prevalence of respiratory symptoms such as shortness of breath, chronic bronchitis, wheezing, and cough among pig workers and animals than in unexposed controls.[2-9]

Gases in pig units arise from the animal's respiration, but the main sources are caused by microbial composition of the feces and urine (i.e., manure decomposition). The primary gaseous contaminants of physiological and physical concern are end products of manure decomposition: ammonia, methane, hydrogen sulfide, and carbon dioxide.

Muehling[10] has given the response of swine to various contaminants: 40,000 ppm of CO_2, an increase in depth and rate of respiration; 50,000 ppm of CH_4, no response from animal (but explosive); 100–200 ppm of NH_3, increased sneezing and salivation and loss of appetite; 20 ppm of H_2S, development of photophobia, anorexia, and nervousness. Drummond et al.[11] found that 50 ppm of NH_3 showed growth and caused mild respiratory disorders.

In a paper addressing the changes in gaseous mass transfer from stored swine manure,[12] a two-film resistance approach is used to calculate the transfer of gaseous contaminants from liquid manure to air. In this approach, the rate of mass transfer from stored manure to air is proportional to the overall mass transfer coefficient, K_o:

$$\text{Mass transfer } (g/s) = (64.31 \cdot 10^{-4}) K_o A C_w \tag{1}$$

where K_o = overall transfer coefficient (g-mol cm^{-2} s^{-1}); A = area of manure pit (cm^2); C_w = concentration of compound in liquid manure, (mg l^{-1}); $64.31 * 10^{-4}$ is a conversion factor related to the overall composition of pig manure, which is found to be $C_{272}H_{445}O_{148}N_{23}S$, in which the molecular weight is equal to 6431 g g-mol^{-1}.[13]

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The overall mass transfer coefficient (K_o) at the air-liquid interface reflects the resistance through both the liquid and gas phases[12]:

$$K_o = (1/K_w + 1/(K \cdot K_g))^{-1} \tag{2}$$

where K_w = liquid-side mass transfer coefficient (g-mol cm^{-2} s^{-1}); K_g = gas-side mass transfer coefficient (g-mol cm^{-2} s^{-1}); $K = (H_i/(P\overline{M})) \cdot 10^6$, in which H_i = Henry's law constant of compound i (atm g-mol^{-1} m^{-3}); P = total pressure (atm); $\overline{M}$ = average molecular weight of swine manure (g g-mol^{-1}).

A well-developed lumped-parameter model[14,15] is used to calculate concentrations of gaseous contaminant within a pig unit and the resulting distribution of swine exposure. The calculated pig exposure is dependent upon chemical mass transfer rates from liquid manure to air, air-exchange rates, and occupancy factors.

On the basis of data derived from the work by Anderson et al. (referred to as the ASBH model),[13] a preliminary data base for the model parameter is presented. The purpose of this paper is to develop an exposure model that quantifies swine exposure to gaseous contaminants emitted from stored manure. The exposure model could estimate swine exposure and inhalation dose factors by combining the emission model and the lumped-parameter model. A sensitivity analysis for identifying the important parameters in the simulation model is also presented.

2. Model development

The lumped-parameter model is used to simulate the transport and distribution of gaseous contaminants inside a typical pig unit consisting of six compartments with a totally slatted floor (*Figure 1*). This unit has one negative pressure ventilation system of three high endwall exhaust fans with a continuous slot inlet. Each compartment is divided into two airspaces of upper and pig occupant airspaces. Each compartment is also divided into three subcompartments and contains six pigs. *Figure 2* illustrates the major components of the lumped-parameter model and shows the airflow pathways.

2.1 Model structure

For each compartment, the lumped-parameter model is used to establish the time-dependent chemical concentrations, by solving the differential equation that balances the time rate of change of contaminant concentration with the instantaneous difference between gains and losses. The mass balance equation for the compartments (*Figures 1* and *2*) can be represented by a first-order vector-matrix differential equation[14,15]:

$$\{\mathrm{d}\mathbf{C}(\mathbf{t})/\mathrm{d}t\} = -[B]\{\mathbf{C}(\mathbf{t})\} + [\mathbf{V}]^{-1}\{\mathbf{G}(\mathbf{t})\},$$
$$\{\mathbf{C}(0)\} = \{\mathbf{C}_0\} \tag{3}$$

where $\{\mathbf{C(t)}\}$ is the vector of gaseous contaminant concentration (ppm); $[\mathbf{V}]^{-1}$ is the inverse diagonal matrix of air volume (m^{-3}); $\{\mathbf{G(t)}\}$ is the vector of gaseous contaminant generation rate (g min^{-1}); and $[\mathbf{B}] = [\mathbf{V}]^{-1}[\mathbf{Q}]$ = system transport matrix (min^{-1}), in which $[\mathbf{Q}]$ = a square airflow matrix with entries Q_{ij} (j = source, i = destination), where

$$Q_{ij} = \begin{cases} -Q_{ij} \text{ for } i \neq j \\ \sum\limits_{\substack{i=1 \\ (i \neq k)}}^{m} Q_{ki} \text{ for } i = j \end{cases} \tag{4}$$

Based on the basic of a simple entrainment concept,[18] the secondary flow rate in a ventilated airspace is entirely

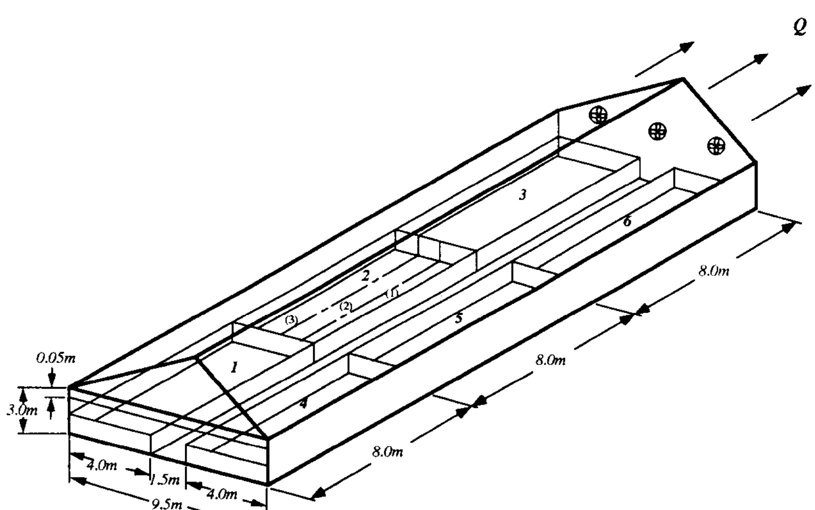


Figure 1. A typical swine confinement unit with a negative ventilation system used in the simulation model. Each pen of the piggery is divided into three subcompartments.

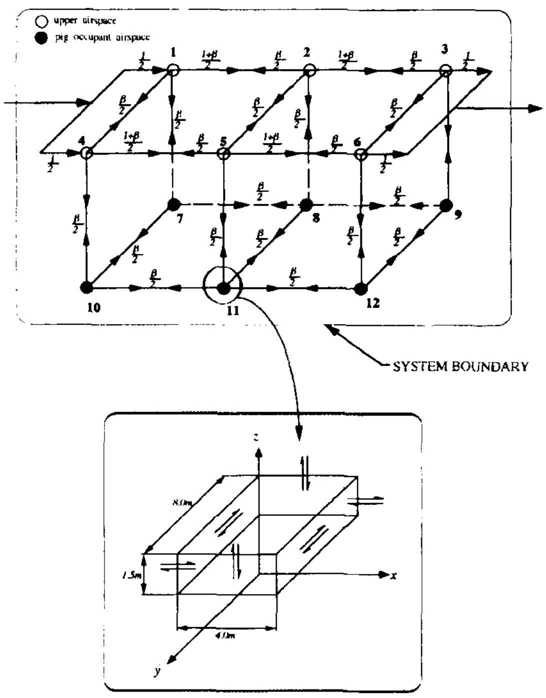


Figure 2. The unit airflow patterns and the control volume of pig compartment. Each compartment is divided into upper and pig occupant airspaces.

induced by the primary flow rate, i.e., by the entrainment in the inlet jets. Therefore, the airflow matrix ([**Q**]) can also be expressed by

$$[\mathbf{Q}] = \mathbf{Q}[\boldsymbol{\beta}] \tag{5}$$

where [**β**] is the square matrix of the entrainment ratio function and β is an entrainment ratio. Equation for the entrainment of jets from long slots has been mathematically expressed as[18] $\beta = \beta Q/Q$ = entrained flow/initial flow $= ((2/K')(X/H_o))$, in which X is the distance from face of outlet (m); H_0 is the width of slot (m); and K' is the proportionality constant (approximately 7). The equilibrium concentration of gaseous contaminant attained can be given as

$$\{\mathbf{C}(\infty)\} = [\mathbf{B}]^{-1}[\mathbf{V}]^{-1}\{\mathbf{G}(\infty)\} \tag{6}$$

where $\{\mathbf{G}(\infty)\}$ is the vector of equilibrium gaseous contaminant generation rate (g min^{-1}).

2.2 Source term vector

The source term vector ($\{\mathbf{G(t)}\}$) is used to account for the input of a gaseous contaminant from the manure pit in each representative pig compartment. The source term for an arbitrary compartment i has the general form

$$G_i(t) = (V_i\phi_i H(t,\tau_i^0,\tau_i^*)/(\tau_i^* - \tau_i^0))C_w \tag{7}$$

where $G_i(t)$ is a time-dependent source term in the ith compartment (g min^{-1}); V_i is the air volume of compartment i (m^3); ϕ_i is the transfer efficiency (g m^{-3} in ventilation air transferred divided by mg L^{-1} of initial concentration in manure) of the chemical from liquid manure to air in compartment i; $H(t,\tau_i^0,\tau_i^*)$ is a function whose value is 1 when t is between τ_i^0 and τ_i^* and zero otherwise (dimensionless); τ_i^0 is the time at which activity in compartment i begins (min); τ_i^* is the time at which activity in compartment i ends (min); and C_w is the contaminant concentration in the manure pit (mg l^{-1}).

The key parameter in equation (7) is the transfer efficiency (ϕ_i). Representative values of these transfer efficiencies based on predicted values for gaseous contaminants (CO_2, CH_4, NH_3, and H_2S) by the ASBH model are listed in *Table 1*. As was shown in equation (2), the overall mass transfer coefficient (K_o) defines the rate of mass transfer between the liquid manure and gas phases. In view of equation (2), K_o depends on the combined mass transfer through liquid and gas boundary layers.

If the bulk fluids are well mixed, then essentially all resistance to mass transfer occurs within the boundary layers on either side of the interface. Under these conditions, Liao and Bundy[12] determined semiempirically that

$$K_w = 0.24M_i^{-0.5}(1.024)^{(T-20)}U^{0.07}H^{-0.85} \tag{8}$$

$$K_g = 8.05\cdot10^{-4}M_i^{-1}Z^{-0.11}S_c^{-0.67} \tag{9}$$

$$K = ((1/K_1\exp(K_2/T_a))M_i)/(P\overline{M}))\cdot10^6 \tag{10}$$

where M_i is the molecular weight of compound i (g g-mole^{-1}); T is temperature (°C); T_a is absolute temperature (°K); U is air velocity (m hr^{-1}); H is depth of the manure pit (m); Z is the length of the manure pit (m); S_c is the gas phase Schmidt number; and K_1 and K_2 are coefficients for predicting the variation of Henry's law constants.

The assumption of a completely mixed air phase is probably fairly reasonable, but complete mixing in the manure is not realistic. Changes in results obtained from this complete-mix model will be examined by varying the value of K_o submitted to the model. This variation has been achieved by introducing a factor (α) ranging in value from 0 to 1 that is used to multiply the value of the clean water mass transfer coefficients as calculated from equations (8)–(9). The condition of the interface is another factor that cannot be modelled exactly, but can be examined by the above-mentioned strategy of varying K_o.

The ASBH model suggests that a factor ranging in value from 0.1 to 0.25 can be used to multiply the value of the clean water mass transfer coefficient as calculated from equations (8)–(10); therefore, equation (2) can be rewritten as

$$K_o = \alpha(1/K_w + 1/(K\cdot K_g))^{-1},\quad 0.1 < \alpha < 0.25 \tag{11}$$

The transfer efficiency is calculated under the assumption that transfer efficiency is proportional to the overall mass transfer coefficient (K_o) at the liquid manure/gas

Table 1. Transfer efficiencies of carbon dioxide, methane, ammonia, and hydrogen sulfide from manure to air at the end of pit-filing periods

Compound	α*	Julian date day	Concentration† Manure (mg/l) (C_w)	Concentration† Air‡ (g/m³) (C_a)	Transfer efficiency (ϕ^m) (C_a/C_w)
Carbon dioxide	0.10	91.3	52.9	1.14	0.02
	0.25	91.3	22.6	1.14	0.05
	0.10	273.8	22.6	0.8	0.03
	0.25	273.8	11.7	0.8	0.07
Methane	0.10	91.3	1.05	0.035	0.033
	0.25	91.3	0.42	0.035	0.083
	0.10	273.8	0.87	0.015	0.017
	0.25	273.8	0.35	0.015	0.04
Ammonia	0.10	91.3	865.94	3.96×10^{-6}	$4.6 \times 10^{-}$
	0.25	91.3	865.35	9.72×10^{-6}	1.1×10^{-8}
	0.10	273.8	865.01	3.61×10^{-6}	4.2×10^{-9}
	0.25	273.8	863.05	9.02×10^{-6}	1.1×10^{-8}
Hydrogen sulfide	0.10	91.3	0.02	5.8×10^{-4}	0.03
	0.25	91.3	0.008	5.8×10^{-4}	0.072
	0.10	273.8	0.017	2.3×10^{-4}	0.014
	0.25	273.8	0.007	2.3×10^{-4}	0.033

*A dimensionless factor.
† Concentration data are adapted from Anderson et al.[13]
‡ Conversion factors for carbon dioxide, methane, ammonia, and hydrogen sulfide from ppm to g/m³ are 1/560, 1/1540, 1/1440, and 1/725, respectively.

boundary based on the predicted values derived from the ASBH model. Therefore,

$$\phi_i^j = \phi_i^m K(j)/K(m) \tag{12}$$

where ϕ_i^j is the transfer efficiency for species j in compartment i, and ϕ_i^m is the transfer efficiency for predicted value as derived from the ASBH model in compartment i, $K(j)$ is the overall mass transfer coefficient for compound j derived from equation (11), and K(m) is the overall mass transfer coefficient derived from the ASBH model.

Equation (12) allows the estimation of relative magnitude of liquid-to-air transfer efficiency of a number of compounds. *Table 2* summarizes the parameters used to calculate the mass transfer coefficient in equation (12) and provides the resulting ratios of $K(j)/K$(m).

For the current estimation, the mass transfer parameters used in equation (12) are evaluated at 20°C. Although this may seem to introduce significant error because of the sensitivity of the Henry's law constant to temperature, it should be recognized that for the compounds considered here the overall mass transfer coefficient is domi-

Table 2. Mass transfer properties of carbon dioxide, methane, ammonia and hydrogen sulfide at 20°C

Compound	k_1* (mg/L-atm)	k_2* (°K)	S	K(j)§ (g-mol/cm²-s)	K(m)¶ (g-mol/cm²-s)	K(j)/K(m)
Carbon dioxide	0.328	2517	0.94†	0.0153	0.00445	3.44
Methane	0.0419	1863	0.84†	0.0254	0.00168	15.16
Ammonia	0.865	4151	0.78†	0.0246	0.00179	13.69
Hydrogen sulfide	0.0199	2226	0.53‡	0.0174	0.00357	4.878

*Adapted from Anderson et al.[13]
† Adapted from Thibodeaux.[17]
‡ Derived from ASHRAE[18] and Treybal.[19]
§ Calculated from equation (11), in which U=0.5 m/s, H=1 m, Z=4 m, P=1 atm, and α=0.25.
¶ Calculated from Anderson et al.[13]

nated by liquid-phase resistance, which tends to be less dependent on temperature than gas-phase resistance.[12] The model also relies on the assumption that mass transfer from a manure pit can be projected with a generalized correlation for turbulent mass transfer.

2.3 Daily air concentration profiles

Equation (3) is solved numerically using the 4th-order Runge-Kutta subroutine and done in double precision with FORTRAN 77. *Figure 3* shows the matrix of entrainment ratio matrix. *Figure 3* indicates that the solution of airflow matrix is by three-dimensional lumped form of control volumes representing the conservation of air mass. *Figure 4* displays the calculated 24-hr air concentration profiles for pig occupant airspaces in six compartments. The parameters used to calculate the ventilation air concentrations of gaseous contaminant attributable to manure pit emission are listed in *Table 3*. The airflow pattern model in *Figure 2* indicates that compartments 4, 5, and 6 are symmetrical to compartments 1, 2, and 3; therefore *Figure 4* shows that the concentration profiles for compartments 4, 5, and 6 are the same as in compartments 1, 2, and 3.

Figure 4 illustrates that the ventilation air concentration profiles of gaseous contaminant in pig occupant compartments are driven by the source term in the manure pit, beginning at 6:00 a.m., when major the activities of pigs in compartments begin. *Figures 4a–4c* show that air concentration profiles of methane, ammonia, and hydrogen sulfide have almost the same trend of concentration histories. The carbon dioxide concentration profiles shown in *Figure 4d* indicate that after the peak concentrations in the ventilation air decay, the concentrations in each compartment become dependent on the other sources, e.g., pig respiration and inflow carbon dioxide concentration from outdoors, etc.

$$\begin{bmatrix}
\frac{1+3\beta}{2} & -\frac{\beta}{2} & 0 & -\frac{\beta}{2} & 0 & 0 & -\frac{\beta}{2} & 0 & 0 & 0 & 0 & 0 \\
-\left(\frac{1+2\beta}{2}\right) & \frac{1}{2}+2\beta & -\frac{\beta}{2} & 0 & -\frac{\beta}{2} & 0 & 0 & -\frac{\beta}{2} & 0 & 0 & 0 & 0 \\
0 & -\left(\frac{1+2\beta}{2}\right) & \frac{1+3\beta}{2} & 0 & 0 & -\frac{\beta}{2} & 0 & 0 & -\frac{\beta}{2} & 0 & 0 & 0 \\
-\frac{\beta}{2} & 0 & 0 & \frac{1+3\beta}{2} & -\frac{\beta}{2} & 0 & 0 & 0 & 0 & -\frac{\beta}{2} & 0 & 0 \\
0 & -\frac{\beta}{2} & 0 & -\left(\frac{1+2\beta}{2}\right) & \frac{1}{2}+2\beta & -\frac{\beta}{2} & 0 & 0 & 0 & 0 & -\frac{\beta}{2} & 0 \\
0 & 0 & -\frac{\beta}{2} & 0 & -\left(\frac{1+2\beta}{2}\right) & \frac{1+3\beta}{2} & 0 & 0 & 0 & 0 & 0 & -\frac{\beta}{2} \\
-\frac{\beta}{2} & 0 & 0 & 0 & 0 & 0 & \frac{3\beta}{2} & -\frac{\beta}{2} & 0 & -\frac{\beta}{2} & 0 & 0 \\
0 & -\frac{\beta}{2} & 0 & 0 & 0 & 0 & -\frac{\beta}{2} & 2\beta & -\frac{\beta}{2} & 0 & -\frac{\beta}{2} & 0 \\
0 & 0 & -\frac{\beta}{2} & 0 & 0 & 0 & 0 & -\frac{\beta}{2} & \frac{3\beta}{2} & 0 & 0 & -\frac{\beta}{2} \\
0 & 0 & 0 & -\frac{\beta}{2} & 0 & 0 & -\frac{\beta}{2} & 0 & 0 & \frac{3\beta}{2} & -\frac{\beta}{2} & 0 \\
0 & 0 & 0 & 0 & -\frac{\beta}{2} & 0 & 0 & -\frac{\beta}{2} & 0 & -\frac{\beta}{2} & 2\beta & -\frac{\beta}{2} \\
0 & 0 & 0 & 0 & 0 & -\frac{\beta}{2} & 0 & 0 & -\frac{\beta}{2} & 0 & -\frac{\beta}{2} & \frac{3\beta}{2}
\end{bmatrix}$$

Figure 3. Matrix of entrainment ratio function.

Table 4 lists the average and maximum concentrations of four compounds in the ventilation air of pig compartments 1, 2, and 3. These concentrations were calculated by using the representative values in *Table 3* and the mass transfer properties in *Table 2*. The average and maximum concentrations calculated refer to the full 24-hr period. The results in *Table 4* indicate that the estimated averaged concentration ratios for carbon dioxide/methane, methane/hydrogen sulfide, and hydrogen sulfide/ammonia are, respectively, on the order of 10^2, 10, and 10^0.

2.4 Occupancy factor and pig exposure

The time-dependent concentration profiles of a chemical in each compartment are used to calculate daily swine exposure and doses through inhalation. It is assumed that each compartment is divided into three subcompartments (*Figure 1*). The daily dose is calculated from the formula

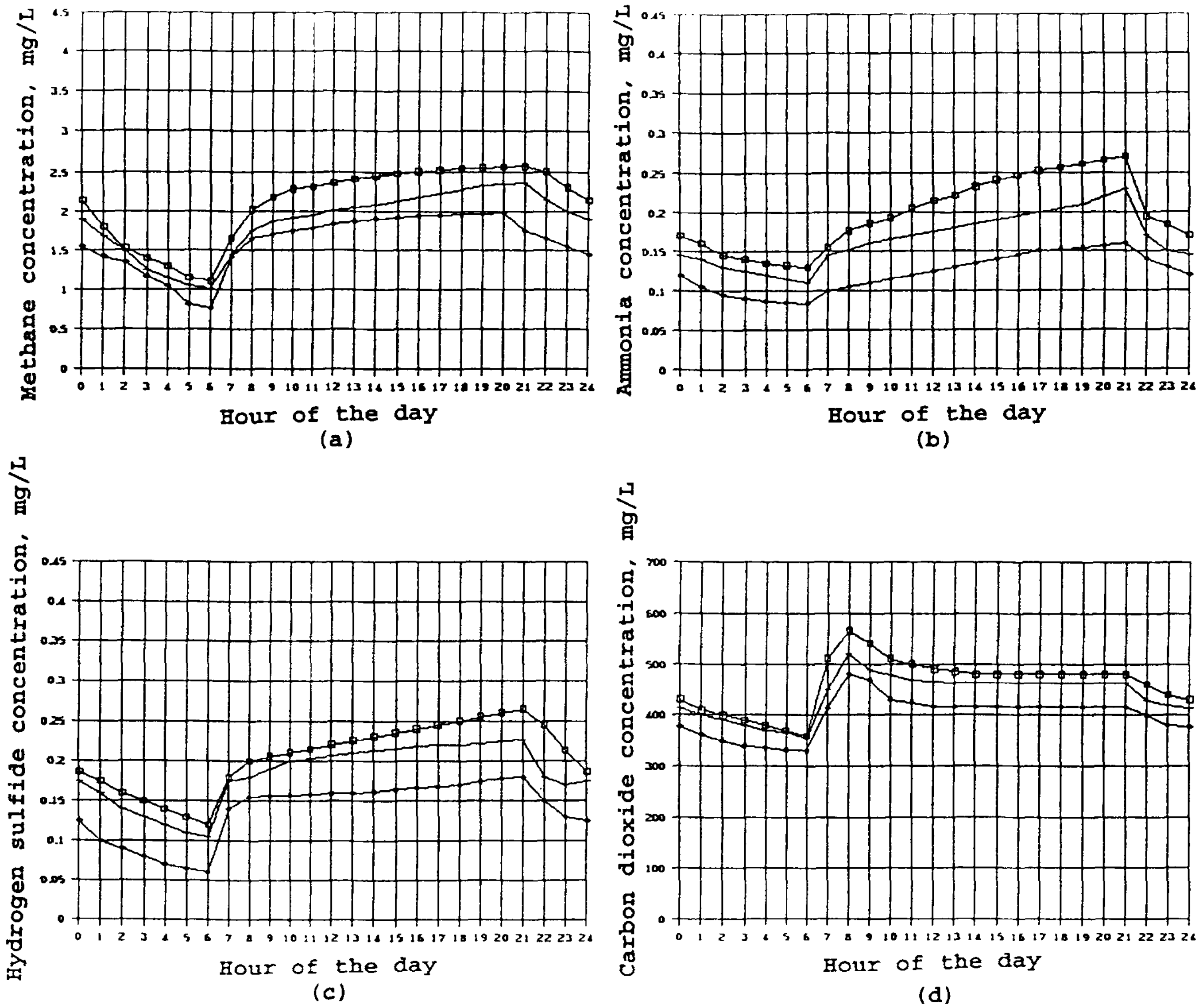
$$D = \gamma/B_w \int_0^{24} \left(\sum_{i=1}^{n} O_{f,i}(t) C_i(t) \right) B_r(t)\,dt \qquad (13)$$

where D is the daily dose rate for a pig in the compartment (mg kg^{-1} d^{-1}); γ is the fraction of the chemical taken into the total lung volume that is available for uptake; B_w is the body weight of the pig (kg); $O_{f,i}(t)$ is the occupancy factor for the probability that one pig is in subcompartment i at time t; $B_r(t)$ is the breathing rate of one pig at time t (l min^{-1}).

Daily dose rates are calculated for three different groups of pig[16]: 1) growing pigs (13–18 weeks), 2) nursery pigs (7–12 weeks), and 3) prenursery pigs (0–6 weeks). The body weights and breathing rates for three groups of pig are listed in *Table 5*.

As for the ventilation air concentration profiles, the assumptions used to calculate daily dose ratios are: 1) All of the chemical taken into the lung is available for uptake (i.e., $\gamma = 1$). 2) Each pig spends 20 min in subcompartment 1 between 6:00 a.m. and 10:00 a.m. 3) Each pig spends an additional 20 min in subcompartment 1 during any 20-hr period (excluding the hours 6:00 a.m. to 10:00 a.m.). 4) Pigs spend 100% of their time in subcompartments 2 and 3 from 9:00 p.m. to 6:00 a.m. and 5) Pigs spend 50% of the time from 6:00 a.m. to 9:00 p.m. in subcompartments 2 and 3.

Figure 5 shows the 24-hr profiles of occupancy factors for one specific pig group in three subcompartments corresponding to the above-noted assumptions. The occupancy factor for each subcompartment is defined as the



□ :Compartments 1,4 +: Compartments 2,5 v:Compartments 3,6

Figure 4. Estimated 24-hr air concentrations of methane, ammonia, hydrogen sulfide, and carbon dioxide in pig occupancy airspaces in six compartments.

probability that one pig is in that subcompartment at any specific time.

For a unit concentration ($C_w = 1$ mg l^{-1}), the doses D calculated from equation (13) can be interpreted as a unit inhalation dose factor for the jth stage group (G_j): $f_i(G_j)$. Thus, for a pig in the jth stage group category, $f_i(G_j) = D(G_j)/C_w$. The inhalation dose factors for each of the three age groups are used to calculate a lifetime-equivalent daily inhalation dose rate or factor (F_i) by taking the weighted sum:

$$F_i = 6/18 f_i(G_3) + 6/18 f_i(G_2) + 12/18 f_i(G_1) \quad (14)$$

where G_1 is for a growing pig, G_2 is for a nursery pig, and G_3 is for a prenursery pig. The lifetime inhalation dose factor (F_i) translates the chemical concentration in the manure pit (C_w, mg l^{-1}) into an equivalent daily dose rate in mg kg^{-1} d^{-1}. The factors 6/18, 6/18, and 12/18 reflect the relative amounts of time that one pig group spends in each stage category.

3. Model analysis

3.1 Calculated inhalation dose factor

Table 6 lists the lifetime inhalation dose factor (F_i) that was calculated with the simulation model applied to the four chemicals under a set of assumptions described above. For ammonia, the inhalation dose factor corresponding to the estimate is 7×10^{-4} (mg kg^{-1} d^{-1})/(mg l^{-1}). For the other gaseous contaminants, the estimates of the inhala-

Table 3. Parameters used to calculate ventilation air concentrations of gaseous contaminant attributable to manure pit emission

Parameter	Description	Representative values	Likely range
Q	Ventilation rate (m^3/s-70 kg pig)		0.01–0.06[†]
	9:00 p.m.–6:00 a.m.	0.02	
	6:00 a.m.–9:00 p.m.	0.05	
V	Airspace volume (Fig. 2)	$4 \times 8 \times 1.5$ m	
C_w	Component concen. in manure pit[†]	$CO_2 = 17.2$ mg/l	11.7–26.6
		$CH_4 = 1.05$ mg/l	0.35–1.05
		$NH_3 = 864.5$ mg/l	863.1–865.9
		$H_2S = 0.02$ mg/l	0.017–0.02
τ°	Time when major activity in compartment begins	6:00 a.m.	
τ^*	Time when major activity in compartment ends	9:00 p.m.	
ϕ^j	Transfer efficiency of species j	$CO_2 = 0.15$	0.07–0.24
		$CH_4 = 0.5$	0.3–0.9
		$NH_3 = 1.5 \times 10^{-7}$	6.9×10^{-8}–5×10^{-7}
		$H_2S = 0.2$	0.07–0.34
β	Entrainment ratio	11.71[‡]	
$[\boldsymbol{\beta}]$	Matrix of entrainment ratio function	*Figure 3*	

[†] From Anderson et al.[13]
[‡] $\beta = (2/k'X/H_0)^{1/2}$, in which H_0 = width of slot = 0.05 m; X = distance from face of outlet = 24 m; and $k' = 7$.

tion dose factor range from 5.61 to 8.1 (mg kg^{-1} d^{-1})/(mg l^{-1}).

Hydrogen sulfide is generally regarded as having lethal potential,[13] therefore *Table 7* summarizes the relative contribution to the lifetime inhalation dose factor from each stage category and occupant compartments for hydrogen sulfide. This table reveals that exposures of larger pigs in subcompartments 2 and 3 are major contributors to lifetime inhalation exposures.

3.2 Comparison with measured results

The results of prediction by the simulation described here are compared with the air concentrations derived from the

Table 4. Average and maximum air concentrations calculated for four chemicals in pig occupant compartments 1, 2, and 3 (*Figure 1*) using representative parameter values listed in *Table 3*

		Air Concentration (mg/l)			
		Upper airspace		Occupant airspace	
Compartment	Compound	Max	Av*	Max	Av
	NH_3	0.18	0.12 ± 0.08	0.27	0.225 ± 0.158
1	CO_2	467.81	425.44 ± 37.98	564.43	462.63 ± 52.15
	CH_4	2.07	1.72 ± 0.37	2.57	211 ± 0.48
	H_2S	0.16	0.12 ± 0.05	0.26	0.206 ± 0.04
	NH_3	0.11	0.09 ± 0.04	0.23	0.166 ± 0.033
2	CO_2	406.56	397.46 ± 32.65	519.44	439.88 ± 42.04
	CH_4	1.97	1.76 ± 0.06	2.37	1.86 ± 0.41
	H_2S	0.14	0.08 ± 0.023	0.22	0.184 ± 0.04
	NH_3	0.07	0.05 ± 0.02	0.16	0.122 ± 0.024
3	CO_2	366.93	329.61 ± 40.01	479.64	399.57 ± 39.65
	CH_4	1.47	1.18 ± 0.28	1.98	1.61 ± 0.35
	H_2	0.11	0.07 ± 0.012	0.18	0.138 ± 0.038

*Av, mean $\pm$ standard deviation ($n = 24$).

Table 5. Body weight and breathing rate for three different stages of pig used in the model simulation

Group	Stage (week)	Body weight* (kg)	Breathing rate (l/min)†	
			Active	Resting
Growing pig	18‡ (13–18)§	70 (35–70)	20	6.6
Nursery pig	12 (7–12)	35 (14–35)	13	4.8
Prenursery pig	6 (0–6)	14 (6–14)	4.2	1.6

* Data are adapted from MWPS.[16]
† Data are adapted and calculated from DeJours[20] and Mount.[21]
‡ Representative values used in the model simulation.
§ Data in parentheses are likely range values.

ASBH model and with the headspace concentrations measured in pilot columns by Liao and Bundy.[12]

Liao and Bundy[12] measured methane, ammonia, carbon dioxide, and hydrogen sulfide concentrations in the headspace of pilot columns containing stored swine manure from under a slated-floor nursery building. All pilot columns were housed in an air-conditioned laboratory. The laboratory ambient temperature was maintained at 15–20°C. The measured air concentrations of methane, ammonia, and carbon dioxide in the headspace were in the ranges of 2.2–2.9, 0.10–0.11, and 470–750 mg/l, respectively. Hydrogen sulfide was not detected during these experimental periods.

The predicted values of air concentrations for methane, ammonia, carbon dioxide, and hydrogen sulfide at the end of pit-filling periods presented in the ASBH model ranged between 22.68 and 55.09 ppm, 0.0057 and 0.014 ppm, 447.36 and 639.57 ppm, and 0.173 and 0.419 ppm, respectively.

On the basis of the values in *Table 4*, the average air concentrations in pig occupant airspace for methane, ammonia, carbon dioxide, and hydrogen sulfide are in the ranges of 1.61–2.11, 0.122–0.225, 399.57–461.63, and 0.138–0.26 mg/l, respectively. The comparisons suggest good agreement with experimental measurements and literature research data. Therefore, the predicted values presented in this paper seem fairly realistic and give some confidence in the simulation model.

The reported mean concentrations of carbon dioxide, methane, ammonia, and hydrogen sulfide in ventilation air and manure based on the suggested value of α in the range of 0.1–0.25 calculated with the ASBH model were 970 mg/m^3 and 27.45 mg/l, 25 mg/m^3 and 0.67 mg/l, 0.007 mg/m^3 and 864.84 mg/l, as well as 0.405 mg/m^3 and 0.013 mg/l, respectively (*Table 1*). Assuming a daily breathing rate of 20 m^3/70 kg of pig, these values translate to inhalation dose factors for carbon dioxide, methane, ammonia, and hydrogen sulfide of 10.09, 10.66, 2.31×10^{-6}, and 8.90 (mg kg^{-1} d^{-1})/(mg/l). These predicted values are high compared to the calculated values of 8.17, 5.61, and 7.41 (mg kg^{-1} d^{-1})/(mg/l) shown in Table 6, except for ammonia (7×10^{-4} mg kg^{-1} d^{-1})/(mg/l).

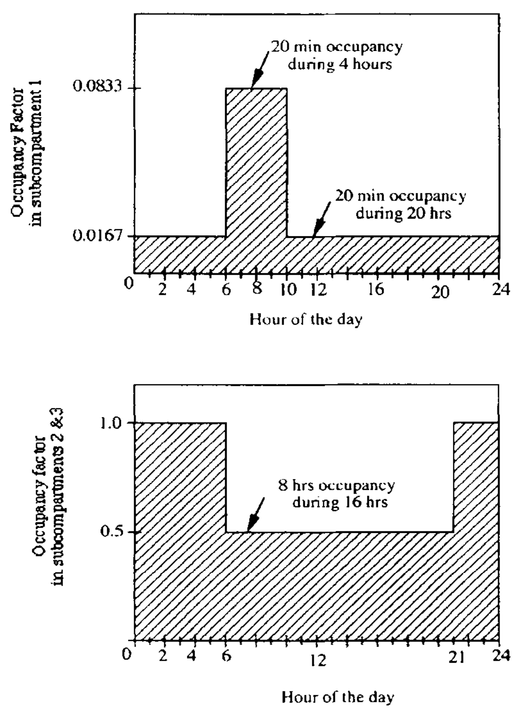


Figure 5. Occupancy factors in one specific pig occupant compartment during 24-hr period corresponding to reference assumptions.

3.3 Sensitivity analysis

A sensitivity analysis is used to identify the relative effect of each parameter on the estimate of the inhalation dose factor. The local relative sensitivity factor is calculated as the change in the overall inhalation dose factor resulting from a 1% increase in an input parameter.

Table 6. Values of lifetime inhalation dose factors (F_i) calculated for four chemicals using lumped-parameter model for swine exposures

Compound	Estimate* (mg kg^{-1} d^{-1})/(mg l^{-1})
Carbon dioxide	8.17
Methane	5.61
Ammonia	7×10^{-4}
Hydrogen sulfide	7.14

* Swine inhalation dose factor attributable to a unit concentration in stored manure.

Table 7. Percentage contribution to lifetime average dose factor for hydrogen sulfide from specific age and subcompartment exposures

Compound	Subcompartment*	% contribution		
		Growing pig	Nursery pig	Prenursery pig
Hydrogen sulfide	1	12.8	6.0	3.14
	2	16.0	8.0	5.16
	3	28.0	15.7	5.20
Total		56.8	29.7	13.5

*See *Figure 1*.

Table 8. Sensitivity of inhalation dose factor to model inputs

Parameter (X)	Local relative sensitivity (dF/dX)
Fraction of chemical inhaled available for uptake	1.0
Transfer efficiency from manure to air	0.82
Ratio of breathing rate to body weight (growing pig)	0.74
Residence time of contaminated air	0.31
Ratio of breathing rate to body weight (nursery pig)	0.25
Volume of confinement unit	0.09
Size of manure pit	0.094
Amount of time spent in each subcompartment	0.29
Ratio of breathing rate to body weight (prenursery pig)	0.023

Table 8 lists the relative local sensitivities for the calculated inhalation dose factor for the four chemicals on the basis of a 1 mg l^{-1} concentration in a manure pit. The results indicate that the inputs with the greatest local sensitivity are the fraction of inhaled chemicals available for uptake, the ratio of breathing rate to body weight, and the transfer efficiency from manure pit to ventilation air.

Other influential parameters include amount of swine waste in the manure pit, the amount of time spent in each subcompartment, and the residence time of the contaminated air.

4. Summary and conclusions

Studies of workers and animals exposed to aerial contaminants in confinement units identified the potential for transferring gaseous compounds from manure pit to ventilation air.

Recognition of the importance of liquid manure to air transfers in aerial contaminant exposure led to efforts to determine the significance of inhalation exposure from gaseous compounds: carbon dioxide, ammonia, methane, and hydrogen sulfide emitted from stored swine manure.

To provide a more comprehensive picture of the relationship between inhalation exposure and concentrations of gaseous contaminant, a time-dependent, lumped-parameter model is used. This model simulates the daily concentrations of gaseous contaminant in each pig occupant compartment. Mass transfer efficiencies from manure pit to ventilation air were derived from literature research values by using mass transfer resistance properties.

One set of assumed data on pig activities in one occupant compartment divided into three subcompartments and a range of exposure parameters combined with the simulation model were used in the paper to calculate estimates of the lifetime daily equivalent swine exposure dose (in mg kg^{-1} d^{-1}) for a unit concentration (mg l^{-1}) in stored manure. Although the comparison indicates good agreement between calculated and measured values, it only serves to verify exposures in each compartment. This research has not been able to find data to verify the calculated values of subcompartment exposure.

A local relative sensitivity analysis is applied to the simulation model to determine the effect of parameter changes on the projected inhalation dose factor. The results indicate that the inhalation dose factor is most sensitive to changes in the uptake fraction in the lung, the ratio of breathing rate to body weight, the liquid manure-to-ventilation air transfer efficiency, and the quantity of manure stored in the pit. This suggests that the full importance of the inhalation exposure may not be fully quantified until the effect of uncertainties and variabilities in these parameters can be better characterised. Therefore, there is a need to conduct a more extensive characterisation of the distribution of exposures within given swine groups. This would require the collection of more detailed information on the characterisation and types of confinement facilities, chemical uptake in the lung, feeding pattern, and occupancy factor.

This exposure model enables engineers to describe the magnitude and distribution of pollution sources, concentrations, and health effects in animal housing.

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References

1. Crook, B., Robertson, J. F., Glass, S. A., Botheroyd, E. M., Lacey, J. and Topping, M. D. Airborne dust, ammonia, microorganisms, and antigens in pig confinement houses and the respiratory health of exposed farm workers. *Am. Ind. Hyg. Assoc. J.* 1991, **52,** 271–279
2. Bongers, P., Houthuijs, D., Remijn, B., Brouwer, R. and Biersteker, K. Lung function and respiratory symptoms in pig farmers. *Br. J. Ind. Med.* 1987, **44,** 819–823
3. Brouwer, R., Biersteker, K., Bongers, P., Remijn, B. and Houthuijs, D. Respiratory symptoms, lung function and IgG4 levels against pig antigens in a sample of Dutch pig farms. *Am. J. Ind. Med.* 1986, **10,** 283–285
4. Donham, K. J., Zavala, D. C. and Merchant, J. A. Respiratory symptoms and lung function among workers in swine confinement buildings: A cross-sectional epidemiological study. *Arch. Environ. Health* 1984, **39,** 96–101
5. Donham, K. J., Zavala, D. C. and Merchant, J. A. Acute effects of the work environment on pulmonary functions of swine confinement workers. *Am. J. Ind. Med.* 1984, **5,** 367–375
6. Harries, M. G. and Cromwell, O. Occupational asthma caused by allergy to pig's urine. *Br. Med. J.* 1982, **284,** 867
7. Holness, D. L., O'blenis, E. L., Sass-Kortsak, A., Pilger, C. and Nethercott, J. R. Effects and dust exposures in hog confinement farming. *Am. J. Ind. Med.* 1987, **11,** 571–580
8. Iverson, L., Korsgaard, D. D. J., Hallas, T. and Jensen, E. J. Respiratory symptoms in Danish farmers: An epidemiological study of risk factors. *Thorax* 1988, **43,** 872–877
9. Katila, M. L., Mantyjarvi, R. A. and Ojanen, T. H. Sensitisation against environmental antigens and respiratory symptoms in swine workers. *Br. J. Ind. Med.* 1981, **38,** 334–338
10. Muehling, A. J. Gases and odors from stored swine waste. *J. Animal Sci.* 1969, **30,** 526–530
11. Drummond, J. G., Curtiss, S. E., Simon, J. and Norton, H. W. Effects of aerial ammonia on growth and health of young pigs. *J. Animal Sci.* 1968, **50,** 1085–1091
12. Liao, C. M. and Bundy, D. S. Bacteria additives to the changes in gaseous mass transfer from stored swine manure. *J. Environ. Sci. Health* 1994, **B29,** 1219–1249
13. Anderson, G. A., Smith, R. J., Bundy, D. S. and Hammond, E. G. Model to predict gaseous contaminants in swine confinement buildings. *J. Agric. Eng. Res.* 1987, **37,** 235–253
14. Liao, C. M. and Bundy, D. S. Quantification of ventilation on distribution of gaseous pollutants emitted from stored swine manure. *J. Environ. Sci. Health* 1995, **B30,** 859–893
15. Liao, C. M. and Feddes, J. J. R. A lumped-parameter model for predicting airborne dust concentration in a ventilated airspace. *Trans. ASAE* 1992, **35,** 1973–1978
16. Midwest Plan Service. *Structures and Environment Handbook*, MWPS-1, Midwest Plan Services, Iowa State University, Ames, IA, 1987, 11th Ed
17. Thibodeaux, L. J. *Chemodynamics*, John Wiley and Sons, New York, 1979
18. ASHRAE. American Society of Heating, Refrigerating, and Air Conditioning Engineers. *ASHRAE Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, New York, 1993
19. Treybal, R. E. *Mass-Transfer Operation*, McGraw-Hill, New York, 1980
20. DeJours, P. *Respiration*, Oxford University Press, New York, 1968
21. Mount, L. E. *The Climatic Physiology of the Pig*, Edward Arnold, London, 1968