validation and uncertainty analysis of an ammonia emission model for broiler litter

Z. Liu, L. Wang-Li, D. B. Beasley, S. B. Shah

ABSTRACT: A mechanistic emission model was previously developed at laboratory scale to estimate ammonia emission fluxes from broiler litter. The overall model inputs include air temperature, air velocity, and litter properties such as litter nitrogen content, moisture content, and pH. The model outputs are predicted ammonia emission fluxes from litter. Considerable uncertainties may exist in measurement values of model inputs and outputs as well as model parameters. The purpose of this study was to perform model validation in the presence of measurement and model parameter uncertainties. A validation metric based on the mean and covariance in the measurement and in the model parameters was used to validate the ammonia emission model of broiler litter. The core model was validated given the uncertainties in the model prediction due to uncertainties of parameters (the Freundlich partition coefficient $K_f$ and the mass transfer coefficient $K_G$) and the uncertainties in the measurements. The significant level for the core model validation was 17.8%. The $K_f$ submodel was validated at the bases of so-called process-based models (Zhang et al., 2006; Ni, 1999). Mechanistic models are the constant, ammonia generation in manure, and ammonia diffusion in manure (Ni, 1999). Mechanistic models are the bases of so-called process-based models (Zhang et al., 2006; Pinder et al., 2004), which consider each of the processes occurring on a typical livestock farm and calculate the resulting ammonia emissions from each. Some models are statistical (Carr et al., 1990; Wheeler et al., 2006; Gates et al., 2007) and simply describe the statistical correlations between ammonia emission and various influencing factors. Mass-balance/N-flow models (Reidy et al., 2008; Dammgen et al., 2002) and inverse dispersion models (Siefert et al., 2004) are calculation models that provide alternative ways to estimate emissions. The National Research Council (NRC) Ad Hoc Committee on Air Emissions from AFOs identified the limitation of available methodologies to estimate national emissions from animal agriculture and recommended that the USEPA and USDA use process-based mathematical models with mass balance constraints to identify, estimate, and guide management changes that decrease emissions from AFOs for regulatory and management programs (NRC, 2003). Broiler chickens are normally raised on litter made up of wood shavings, sawdust, or peanut hulls above an earthen floor. The litter serves as a manure absorbent. The mixture of litter and manure, referred to as built-up litter, is a significant source of ammonia emissions in broiler houses. Many studies have been reported throughout the world on ammonia emissions from broiler houses, and wide variations have been found among different studies. Measurements from broiler houses indicated that ammonia emission fluxes varied 55-fold, from 15.3 to 848.8 mg NH$_3$-N h$^{-1}$ m$^{-2}$ (Redwine et al., 2002). Variations in ammonia emissions result from the dependence of ammonia emissions on seasonal and regional conditions, house design, and management practices. The mechanisms related to ammonia emissions from manure involve many processes and have been summarized by Ni (1999). Theoretically, the processes involved in ammonia emissions from litter include conversion of uric acid to urea, hydrolysis of urea, enzymatic and microbial generation of...
ammonia, diffusion of ammonia in litter, partitioning between adsorbed and dissolved phase ammonium ions, equilibrium of ammonia in aqueous solution, partitioning between dissolved phase and gaseous phase ammonia, and convective mass transfer of ammonia gas from the surface into the free air stream. Factors that may influence ammonia emissions from broiler litter include air and litter temperature, ventilation rate, air velocity across the litter surface, litter pH, litter nitrogen content, and litter moisture content.

A mechanistic emission model was previously developed by the authors (Liu et al., 2009) at laboratory scale to estimate ammonia emission fluxes from broiler litter. The overall model inputs include air temperature, air velocity, and litter properties such as litter nitrogen content, moisture content, and pH. The model outputs are the predicted ammonia emission fluxes from litter. Model validation is generally a recurrent activity in a phase of model development (Ni et al., 2000). A common method of validation is the simple comparison of model predictions to experimental measurements through a graph. However, there has been an increased concern on the role of uncertainty in model validation in the literature (Warren-Hicks et al., 2002; Hills and Trucano, 1999; Easterling, 2003). Considerable uncertainties may exist in measurement values of model inputs and outputs as well as model parameters. Because of these uncertainties, big difference may be observed between the model predictions and the experimental measurements, even for actually valid models. The presence of uncertainty complicates the model validation process (Hills, 2006).

The objective of this study was to perform validation on an emission model for broiler litter in the presence of measurement and model parameter uncertainty. A validation metric, introduced by Hills (2006), based on the mean and covariance in the measurement and in the model parameters was used to quantify and evaluate the distance between model predictions and experimental measurements.

**MODEL DESCRIPTION**

**MODEL STRUCTURE**

The emission model includes a core emission flux equation, which was developed based on the two-film theory (Welty et al., 1984), and several submodels. In the core emission flux equation (eq. 1), the ammonia flux is a function of the mass transfer coefficient \(K_G\), the gas phase ammonia concentration in equilibrium with dissolved ammonia in litter \(C_{g,0}\), the ventilation rate \(Q\), and the emission surface area \(A\) (Liu et al., 2009):

\[
J = \left( \frac{1}{Q/A} + \frac{1}{K_G} \right)^{-1} C_{g,0}
\]  

where

\[
J = \text{emission flux (mg m}^{-2}\text{ h}^{-1})
\]

\[
Q = \text{ventilation rate of the broiler house (m}^3\text{ h}^{-1})
\]

\[
A = \text{emission surface area of litter (m}^2\text{)}
\]

\[
K_G = \text{overall mass transfer coefficient in gas phase (m h}^{-1})
\]

\[
C_{g,0} = \text{gas phase ammonia concentration in equilibrium with dissolved ammonia in litter (mg m}^{-3})
\]

To estimate the ammonia flux, the most important task is to determine \(C_{g,0}\) and \(K_G\). The value of \(C_{g,0}\) is dependent on the equilibrium between gas phase ammonia and the total ammoniacal nitrogen (TAN) content in the litter. Because of litter moisture content, TAN in litter partitions into the adsorbed and dissolved phases. Dissolved ammonia in litter can exist in the form of ammonium ions \((NH_4^+\)\) and free ammonia \((NH_3)\), and adsorbed ammonia is mainly in the form of \(NH_4^+\). The processes related to ammonia emissions from broiler litter are illustrated in figure 1.

The value of \(C_{g,0}\) can be estimated using the following submodels (Liu et al., 2009):

\[
C_{g,0} = \frac{17}{14} \frac{[NH_3-N]_l}{K_h}
\]

\[
[NH_3-N]_l = 1000 \times \frac{\rho_{H_2O}}{MC} \times [TAN] \times F_c
\]

\[
F_c = \frac{1}{1 + 10^{-pH/\alpha K_{d0}}}
\]

\[
\alpha = \left(1 + K_f \frac{\rho_{H_2O}}{MC}\right)^{-1}
\]

\[
K_f = \frac{[NH_4^+-N]}{[NH_3-N]_l} \times 1000
\]

where

\[
[NH_3-N]_l = \text{concentration of dissolved phase NH}_3\text{-N (mg L}^{-1})
\]

\[
[NH_4^+-N] = \text{concentration of dissolved phase NH}_4^+\text{-N (mg L}^{-1})
\]

**Figure 1. Processes related to ammonia emissions from broiler litter.**
K

h

= Henry’s constant (dimensionless)
MC

= moisture content of litter (w/w%, dry basis)
ρ

H₂O

[TAN]

= density of water (kg L⁻¹)
F

c

= corrected fraction of free ammonia nitrogen over TAN (dimensionless)
pH

= pH value of litter (dimensionless)
K

d0

= dissociation constant of ammonia in water (dimensionless)
α

= ratio of the dissociation constant in manure over that in water (reported value of α is from 0.2 to 1; Hashimoto to and Ludington, 1971; Zhang, 1992; van der Molen et al., 1990; Liang et al., 2002; Arogo et al., 2003)
K

f

= Freundlich partition coefficient (L kg⁻¹)

Adsorbed NH₄⁺-N = amount of adsorbed NH₄⁺-N in litter solid (μg g⁻¹, dry basis).

The dissociation constant in water solution (Kd0) is a function of temperature (K). It can be expressed with the following semi-empirical equation (Kamin et al., 1979):

\[
\log K_{d0} = -0.0918 - 2729.92/T \\
(\text{at } 25°C, K_{d0} = 10^{-9.3})
\]  

(7)

Hales and Drewes (1979) developed an empirical equation to calculate \( K_h \) in non-dimensional form as a function of temperature (K):

\[
\log K_h = -1.69 + 1477.7/T
\]  

(8)

SUBMODELS OF \( K_f \) AND \( K_G \)

Based on the experimental measurements from a dynamic flow-through chamber, the following regression submodel of \( K_f \) as function of litter pH value (concentration of hydrogen ion [H⁺]) and temperature (°C) was obtained (Liu et al., 2009):

\[
K_f = C_1[H^+]^a(T)^b
\]  

(9)

where \( C_1, a, b \) are regression coefficients: \( C_1 = 0.00672, a = -0.412, \) and \( b = -0.759. \) The pH was in the range from 7.4 to 9.0, and temperature was in the range from 8°C to 30°C in the submodel development.

Determination of \( K_G \) is largely empirical. The reported values of these coefficients vary widely, ranging from 0.005 to 42 m h⁻¹ (Ni, 1999). Review of the existing ammonia emission models shows that the mass transfer coefficients were usually calculated as a function of air velocity and temperature (Ni, 1999; Zhang, 1992). Based on the experimental measurements from a wind tunnel, the following regression submodel of \( K_G \) as function of air velocity (U) and air temperature (T) was obtained (Liu et al., 2008):

\[
K_G = C_2(U)^c(T)^d
\]  

(10)

where \( C_2, c, d \) are regression coefficients, and the unit for temperature is °C. The results for the constant \( C_2 \) and exponents \( c \) and \( d \) are reported in table 1. The air velocity was in the range from 0.25 to 2.0 m s⁻¹, and temperature was in the range from 9°C to 30°C in the submodel development.

The overall model structure is shown in figure 2. The input parameters are litter TAN content, litter pH, litter moisture content, ambient temperature, air velocity at litter surface, and Q/A ratio.

VALIDATION METRICS

UNCERTAINTIES IN MODEL VALIDATION

The sources of uncertainty in model validation practices mainly include measurement uncertainties, model parameter uncertainties, and uncertainties associated with the model form error (Hills, 2006). In order to perform model validation in the presence of measurement and model parameter uncertainties, we need to evaluate whether the effects of uncertainties associated with the model form error are significant as compared with that of measurement uncertainties and model parameter uncertainties. To quantitatively test for model validity, a measure of the distance between the model predictions and the experimental measurements is needed. In an n-dimensional space, the n measurements and the corresponding n model predictions can be represented by two points. The effects of uncertainties from measurements and model parameters can be plotted around the two points respectively in the form of isoprobability density function (iso-PDF) surfaces, which can be estimated and propagated through the model using the multivariate, first-order sensitivity analysis presented by Hills and Trucano (2001). When using a statistical test to evaluate the distance between model predictions and experimental measurements in the presence of uncertainties, it is common practice not to reject the model unless there is less than a 5% probability of rejecting a valid model (type I error) (Hills, 2006). In other words, the model is rejected if the significance level is less than 5%. Hills (2006) also suggested that a researcher can have confidence in the model if the significance level is larger than 33% (approximately one standard deviation for a normal distribution).

The \( r^2 \) METRIC

A validation metric based on the mean and covariance in the measurement and in the model parameters, which was
introduced by Hills (2006), was used to quantify the distance between the model predictions and the experimental measurements in $n$-dimensional space, where $n$ is the number of measurements and corresponding predictions. This weighted least squares metric ($r^2$) is defined in equations 11 to 14. In these equations, $X_{\text{model}}$ is the vector of model predictions and $X_{\text{exp}}$ is the corresponding vector of experimental measurements. The matrix $\text{cov}(X_{\text{model}} - X_{\text{exp}})$ is the covariance of the difference between model predictions and experimental measurements. It is the sum of the covariance matrices for each when the uncertainties in the measurements are independent of the uncertainties in the model predictions. The uncertainties in the model predictions can be estimated and propagated through the model using a multivariate, first-order sensitivity analysis presented by Hills and Trucano (2001). Assuming that the differences between the model predictions and the experimental measurements are normally distributed, the covariance matrix for these differences is adequately represented, $r^2$ will be distributed as a $\chi^2(df)$ distribution where $df$ is the degrees of freedom.

$$r^2 = (X_{\text{model}} - X_{\text{exp}})^T \times \text{cov}^{-1}(X_{\text{model}} - X_{\text{exp}}) \times (X_{\text{model}} - X_{\text{exp}})$$

$$\text{cov}(X_{\text{model}} - X_{\text{exp}}) = \text{cov}(X_{\text{model}}) + \text{cov}X_{\text{exp}}$$

$$\text{cov}(X_{\text{model}}) = \nabla_\theta \times \text{cov}(\theta)[\nabla_\theta X]^T$$

where

- $\theta =$ vector of model parameters
- $\nabla_\theta X =$ sensitivity matrix with $n$ measurements for a model with $p$ parameters, which is given by:

$$\nabla_\theta X = \begin{bmatrix} \frac{\partial X_1}{\partial \theta_1} & \frac{\partial X_1}{\partial \theta_2} & \cdots & \frac{\partial X_1}{\partial \theta_p} \\ \frac{\partial X_2}{\partial \theta_1} & \frac{\partial X_2}{\partial \theta_2} & \cdots & \frac{\partial X_2}{\partial \theta_p} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial X_n}{\partial \theta_1} & \frac{\partial X_n}{\partial \theta_2} & \cdots & \frac{\partial X_n}{\partial \theta_p} \end{bmatrix}$$

**EXPERIMENT METHODS**

**VALIDATION OF CORE MODEL CONSIDERING UNCERTAINTIES OF $K_f$ AND $K_G$**

The ammonia emission fluxes from ten different litter samples were measured in the dynamic flux chamber, and the results were used for validation of the core model considering the uncertainties of $K_f$ and $K_G$. The properties of the ten litter samples are listed in table 2, in which TAN and litter moisture contents are expressed on a dry basis.

Ammonia concentration in the chamber was measured with a chemiluminescence ammonia analyzer (model 17C, Thermo Environmental Instruments, Franklin, Mass). Details of the measurements of ammonia emission fluxes using the dynamic flux chamber can be found in Liu et al. (2009). For each litter sample, three replicate measurements were taken at the designed condition ($Q = 74$ L min$^{-1}$, $T = 22$ °C), and the average values were used in the validation of the model. The measured ammonia emission fluxes were in the range from 8 to 1124 mg m$^{-2}$ h$^{-1}$, and the standard deviation of ammonia fluxes ($\sigma_f$) estimated from the replicate measurements was 233 mg m$^{-2}$ h$^{-1}$. The value of $\sigma_f$ was expected to represent the uncertainty of the experimental measurements ($X_{\text{exp}}$) due to nuisance factors or instrumental noises. The average value of $K_f$ was 2.08 L kg$^{-1}$ for the ten litter samples, and the standard deviation ($\sigma_{K_f}$) was 1.12 L kg$^{-1}$. The average value of $K_G$ was estimated to be 8.11 m h$^{-1}$, and the standard deviation ($\sigma_{K_G}$) was 1.86 m h$^{-1}$. The uncertainties of the model parameters ($\theta$) were represented by $\sigma_{K_f}$ and $\sigma_{K_G}$. The metric defined in equations 11 to 14 was used to validate the emission model in the presence of the uncertainties of $K_f$ and $K_G$. Assuming that $K_f$ and $K_G$ are uncorrelated and normally distributed, the covariance matrices of the experimental measurements and the model parameters are:

$$\text{cov}(X_{\text{exp}}) = \begin{bmatrix} 233^2 & 0 & \cdots & 0 \\ 0 & 233^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 233^2 \end{bmatrix}$$

$$\text{cov}(\theta) = \begin{bmatrix} K_f \\ K_G \end{bmatrix} = \begin{bmatrix} 1.12^2 & 0 \\ 0 & 1.86^2 \end{bmatrix}$$

Since the $K_f$ value was estimated from ten measurements, the total degree of freedom is 10 - 1 = 9. Therefore, $r^2$ was distributed as a $\chi^2(9)$ distribution.

**VALIDATION OF $K_f$ SUBMODEL CONSIDERING UNCERTAINTIES OF $pH$ AND TEMPERATURE**

Two different litter samples were used for validation of the $K_f$ submodel considering uncertainties of pH and temperature. The properties of the two litter samples are listed in table 3, in which TAN and litter moisture contents are expressed on a dry basis.

The submodel of $K_f$ as a function of litter pH value (concentration of hydrogen ion [H$^+$]) and temperature (°C) (eq. 9) was tested in the wind tunnel. Ammonia concentrations at the outlet and inlet of the wind tunnel were measured

<table>
<thead>
<tr>
<th>Litter Sample</th>
<th>TAN (µg g$^{-1}$)</th>
<th>pH</th>
<th>Moisture Content (w/w %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3787</td>
<td>8.9</td>
<td>33.4</td>
</tr>
<tr>
<td>2</td>
<td>1751</td>
<td>9.0</td>
<td>29.6</td>
</tr>
<tr>
<td>3</td>
<td>3961</td>
<td>7.6</td>
<td>35.1</td>
</tr>
<tr>
<td>4</td>
<td>2605</td>
<td>8.7</td>
<td>21.8</td>
</tr>
<tr>
<td>5</td>
<td>4650</td>
<td>8.1</td>
<td>21.7</td>
</tr>
<tr>
<td>6</td>
<td>3405</td>
<td>7.4</td>
<td>28.1</td>
</tr>
<tr>
<td>7</td>
<td>4607</td>
<td>7.8</td>
<td>36.9</td>
</tr>
<tr>
<td>8</td>
<td>3033</td>
<td>8.1</td>
<td>32.9</td>
</tr>
<tr>
<td>9</td>
<td>4795</td>
<td>6.3</td>
<td>22.9</td>
</tr>
<tr>
<td>10</td>
<td>1908</td>
<td>8.8</td>
<td>34.4</td>
</tr>
</tbody>
</table>

Table 2. Properties of the ten litter samples used for validation of core model.
Table 3. Properties of the two litter samples used for validation of the K_f and K_G submodels.

<table>
<thead>
<tr>
<th>Litter Sample</th>
<th>TAN (μg g⁻¹)</th>
<th>pH</th>
<th>Moisture Content (w/w %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4501</td>
<td>8.5</td>
<td>29.8</td>
</tr>
<tr>
<td>B</td>
<td>9176</td>
<td>8.6</td>
<td>56.7</td>
</tr>
</tbody>
</table>

using the chemiluminescence ammonia analyzer (model 17C, Thermo Environmental Instruments, Franklin, Mass). Details of the measurements of ammonia emission fluxes using the wind tunnel can be found in Liu et al. (2009). The validation metric \( r^2 \) was calculated at various combinations of pH and temperature. The uncertainty of pH was determined by the accuracy of the pH meter (\( \sigma_{\text{pH}} = 0.1 \)), and the uncertainty of temperature was determined by the resolution of the thermometer (\( \sigma_T = 0.5^\circ \text{C} \)).

VALIDATION OF K_G SUBMODEL CONSIDERING UNCERTAINTIES OF AIR VELOCITY AND TEMPERATURE

The submodel K_G as function of air velocity and temperature (eq. 10) was tested in the wind tunnel using litters A and B. The validation metric \( r^2 \) was calculated at various combinations of air velocity and temperature. A hotwire anemometer (model 641-18-LED, Dwyer Instruments, Michigan City, Ind.; range: 0 to 10 m s⁻¹; accuracy: 3% full scale) was used to measure air velocity in the wind tunnel at a height of 0.13 m above the litter surface. The uncertainty of air velocity was determined from the standard deviation of repeated measurements (\( \sigma_u = 0.1 \) m s⁻¹), and the uncertainty of temperature was determined by the resolution of the thermometer (\( \sigma_T = 0.5^\circ \text{C} \)).

RESULTS AND DISCUSSIONS

The measured and model-predicted ammonia emission fluxes for the ten litter samples are compared in figure 3. For litters 1 and 2, the model overestimated ammonia emission fluxes. This is believed to be due to the high pH values of litters 1 and 2. In the model prediction, average K_f was used (2.08 L kg⁻¹). However, according to equation 9, the high pH of litter 1 and 2 can result in much high K_f values, which lead to much lower ammonia emission fluxes than the model-predicted values. The overall validation results of the core model give \( r^2 = 12.68 \) and \( P (r^2 > 12.68) = 0.178 \). The significance level indicated that, given the uncertainties in the model prediction due to parameter uncertainties of K_f and K_G and the uncertainties in the measurements, the probability of a valid model given this large or larger value in the weighted distance squared is 17.8%. This is more significant than the 5% specified earlier to reject the model outright.

The validation results of the K_f submodel are presented in table 4. It can be seen that, for all six groups of measurements, the K_f submodel passed the validation test (p > 5%) at the given uncertainty level of pH and temperature.

The validation results of the K_G submodel at selected combinations of air velocity and temperature are presented in table 5. It can be seen that, for 6 out of 12 groups of measurements, the K_G submodel passed the validation test (p > 5%) at the given uncertainty level of air velocity and temperature. The measurement data for litter A were used in the development of the K_G submodel. For litter A, at air velocities of 1.24 and 1.56 m s⁻¹, the submodel failed the validation test and underestimated the K_G value. At air velocities of 1.73 and 1.99 m s⁻¹, the submodel failed the validation test and overestimated the K_G value.

The measured and model-predicted K_G for litter A at \( T = 25^\circ \text{C} \) are compared in figure 4. It can be seen that, when the air velocity was above 1.6 m s⁻¹, the measured emission

![Figure 3. Comparison of measured and model-predicted ammonia emission fluxes for the ten litter samples (K_f = 2.08 L kg⁻¹, K_G = 8.11 m h⁻¹).](image-url)

Table 4. Validation results of the K_f submodel.

<table>
<thead>
<tr>
<th>pH</th>
<th>Temperature (°C)</th>
<th>K_f (L kg⁻¹)</th>
<th>No. of Measurements</th>
<th>Validation Metric (r²)</th>
<th>Significance Level (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5 ±0.1</td>
<td>20.0 ±0.5</td>
<td>2.18</td>
<td>3</td>
<td>4.17</td>
<td>0.244</td>
</tr>
<tr>
<td>8.5 ±0.1</td>
<td>21.1 ±0.5</td>
<td>2.09</td>
<td>6</td>
<td>6.74</td>
<td>0.345</td>
</tr>
<tr>
<td>8.5 ±0.1</td>
<td>21.7 ±0.5</td>
<td>2.05</td>
<td>3</td>
<td>5.83</td>
<td>0.120</td>
</tr>
<tr>
<td>8.6 ±0.1</td>
<td>22.8 ±0.5</td>
<td>2.23</td>
<td>4</td>
<td>3.86</td>
<td>0.425</td>
</tr>
<tr>
<td>8.6 ±0.1</td>
<td>24.6 ±0.5</td>
<td>2.10</td>
<td>3</td>
<td>2.40</td>
<td>0.494</td>
</tr>
<tr>
<td>8.6 ±0.1</td>
<td>27.7 ±0.5</td>
<td>1.92</td>
<td>3</td>
<td>2.98</td>
<td>0.394</td>
</tr>
</tbody>
</table>

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Table 5. Validation results of the KG submodel.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Litter</th>
<th>Air Velocity (m s⁻¹)</th>
<th>Temperature (°C)</th>
<th>KG (m h⁻¹)</th>
<th>No. of Measurements</th>
<th>Validation Metric (r²)</th>
<th>Significance Level (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
<td>0.07 ±0.10</td>
<td>19.4 ±0.5</td>
<td>12.13 ±0.10</td>
<td>3</td>
<td>2.00 ±0.02</td>
<td>0.572 ±0.03</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>0.12 ±0.10</td>
<td>16.7 ±0.5</td>
<td>8.95 ±0.05</td>
<td>3</td>
<td>2.41 ±0.10</td>
<td>0.492 ±0.02</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>1.20 ±0.10</td>
<td>14.1 ±0.5</td>
<td>16.33 ±0.10</td>
<td>4</td>
<td>3.68 ±0.10</td>
<td>0.451 ±0.02</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>1.24 ±0.10</td>
<td>21.1 ±0.5</td>
<td>9.84 ±0.05</td>
<td>3</td>
<td>45.14 ±0.01</td>
<td>&lt;0.001 ±0.001</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>1.56 ±0.10</td>
<td>20.8 ±0.5</td>
<td>10.77 ±0.05</td>
<td>3</td>
<td>22.69 ±0.10</td>
<td>&lt;0.001 ±0.001</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>1.72 ±0.10</td>
<td>20.0 ±0.5</td>
<td>11.67 ±0.05</td>
<td>3</td>
<td>2.60 ±0.10</td>
<td>0.457 ±0.02</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>1.73 ±0.10</td>
<td>10.5 ±0.5</td>
<td>26.67 ±0.10</td>
<td>3</td>
<td>8.48 ±0.10</td>
<td>0.037 ±0.01</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>1.99 ±0.10</td>
<td>25.8 ±0.5</td>
<td>8.81 ±0.05</td>
<td>3</td>
<td>5.28 ±0.01</td>
<td>0.164 ±0.001</td>
</tr>
<tr>
<td>B</td>
<td>B</td>
<td>0.16 ±0.10</td>
<td>24.6 ±0.5</td>
<td>3.65 ±0.05</td>
<td>3</td>
<td>1.13 ±0.10</td>
<td>0.968 ±0.01</td>
</tr>
<tr>
<td>B</td>
<td>B</td>
<td>0.39 ±0.10</td>
<td>25.4 ±0.5</td>
<td>5.42 ±0.05</td>
<td>4</td>
<td>5.06 ±0.10</td>
<td>0.281 ±0.01</td>
</tr>
<tr>
<td>B</td>
<td>B</td>
<td>0.62 ±0.10</td>
<td>24.0 ±0.5</td>
<td>6.73 ±0.05</td>
<td>3</td>
<td>11.01 ±0.10</td>
<td>0.012 ±0.001</td>
</tr>
<tr>
<td>B</td>
<td>B</td>
<td>1.20 ±0.10</td>
<td>27.8 ±0.5</td>
<td>6.85 ±0.05</td>
<td>3</td>
<td>119.29 ±0.10</td>
<td>&lt;0.001 ±0.001</td>
</tr>
</tbody>
</table>

A validation metric based on the mean and covariance in the measurements and in the model parameters was used to validate the ammonia emission model of broiler litter. The core model was validated given the uncertainties in the model predictions, due to parameter uncertainties of $K_f$ and $K_G$, and the uncertainties in the measurements. The significant level for the core model validation was 17.8%. The $K_f$ submodel was validated at the given uncertainties of pH and temperature, and the significant levels were from 12.0% to 49.4%, which provided high confidence for the $K_f$ submodel. At the given uncertainty levels of air velocity and temperature, the $K_G$ submodel passed the validation test ($p > 5\%$) when air velocities were low and failed the validation test ($p < 5\%$) when air velocities were high. The failure of the $K_G$ submodel at high air velocities may have been caused by significant loss of nitrogen and moisture content from the litter surface. It indicated the limitation of the model when handling dynamic situations (a changing source). In addition, extrapolation of the model to actual broiler houses still requires more work. External validation needs to be performed using actual broiler house measurement data.

**CONCLUSION**

A validation metric based on the mean and covariance in the measurements and in the model parameters was used to validate the ammonia emission model of broiler litter. The core model was validated given the uncertainties in the model predictions, due to parameter uncertainties of $K_f$ and $K_G$, and the uncertainties in the measurements. The significant level for the core model validation was 17.8%. The $K_f$ submodel was validated at the given uncertainties of pH and temperature, and the significant levels were from 12.0% to 49.4%, which provided high confidence for the $K_f$ submodel. At the given uncertainty levels of air velocity and temperature, the $K_G$ submodel passed the validation test ($p > 5\%$) when air velocities were low and failed the validation test ($p < 5\%$) when air velocities were high. The failure of the $K_G$ submodel at high air velocities may have been caused by significant loss of nitrogen and moisture content from the litter surface. It indicated the limitation of the model when handling dynamic situations (a changing source). In addition, extrapolation of the model to actual broiler houses still requires more work. External validation needs to be performed using actual broiler house measurement data.

**REFERENCES**


