Mass transfer coefficients of ammonia for liquid dairy manure

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HIGHLIGHTS

- The mass transfer coefficient (KOL) of ammonia (NH3) increased with liquid temperature (Tl) and air velocity (Vair).
- The KOL decreased with increases in air temperature (Ta), and total solids (TS) concentration.
- The KOL sensitivity to key factors, in descending order, was: Tl, Ta, Vair and TS concentration.

ARTICLE INFO

Article history:
Received 10 February 2012
Received in revised form 18 June 2012
Accepted 24 July 2012

Keywords:
Ammonia emissions
Overall mass transfer coefficient (KOL)
Process-based models
Convective emission chamber
Dairy manure

ABSTRACT

Available data indicate that 75–80% of total nitrogen entering a dairy operation is lost as ammonia (NH3) via manure storage systems such as anaerobic lagoons. Direct measurement of NH3 emissions from manure holding systems can be complicated and expensive; however, process-based emission models can provide a cost-effective alternative for estimating NH3 emissions. The overall NH3 mass transfer coefficient (KOL) is an important component of any NH3 emission process-based model. Models relying purely on theoretically-derived mass transfer coefficients have not adequately predicted NH3 emissions from livestock manure, and these values are lacking in general for liquid dairy manure handling systems. To provide critically needed KOL data for dairy facilities, this study directly measured NH3 loss from dilute dairy manure slurries placed in a laboratory convective emission chamber to determine realistic NH3 KOL values under conditions typically experienced in the Pacific Northwest. The KOL values increased as liquid temperature and air velocity increased and decreased as air temperature and total solids content increased, exhibiting an overall range of 1.41 × 10−6–3.73 × 10−6 m s−1. These values were then used to develop a non-linear empirical model of KOL for dilute dairy manure slurries (R2 = 0.83). The KOL exhibited sensitivity to the four model parameters considered in descending order: liquid manure temperature, ambient air temperature, wind or air velocity, and total solids concentration. The suite of KOL values applicable to liquid dairy manure and the establishment of an empirical model that yields accurate KOL estimates under a range of conditions for use in process-based models provide valuable tools for predicting NH3 emissions from dairy operations.

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1. Introduction

Agriculture is the largest source of global ammonia (NH3) emissions, with livestock production accounting for ~80% of this total flux (De Visscher et al., 2002; Aneja et al., 2000; Sommer and Hutchings, 1995; Battye et al., 1994). Seventy to 85% of the total nitrogen (total-N) entering an anaerobic lagoon can be lost via gaseous emissions, as opposed to 10–55% for other types of livestock manure storage systems (MWPS, 2001). Similarly, the US EPA estimates that dairy lagoons lose 71% of total-N when calculating NH3 volatilization as part of the National Emission Inventory (EPA, 2004). Thus, it is clear that anaerobic lagoons significantly contribute to NH3 emissions originating from dairy operations. This is a concern because emitted NH3 not only pollutes the environment (Ullman and Mukhtar, 2007; Paerl and Whitall, 1999), but the corresponding N loss also lowers the fertilizer-value of the residual manure (Vaddella et al., 2011; Ndegwa et al., 2008).

Determining NH3 emissions from agricultural facilities is critical to appropriately regulate emissions from livestock operations to protect the environment. Direct measurement of NH3 fluxes from manure storage facilities, however, can be challenging, time consuming, and expensive (Liang et al., 2002). Since NH3...
volatilization is governed by both manure characteristics and environmental or meteorological conditions, this onerous task has
to be performed for each separate livestock operation because no
two facilities will be similar in all respects. Process-based emission
models offer an alternative, cost-effective approach for estimating
NH3 emissions from such systems, because process-based models
generally only require values for key manure, environmental and
meteorological parameters to effectively predict NH3 volatilization
rates for the system in question.

A generic process-based model for NH3 emissions from bulk
liquid manure can be expressed as:

\[
Q_a = K_{OL} A ([NH_3]_L - [NH_3]_a)
\]  

(1)

Where \(Q_a\) = ammonia flux (g s\(^{-1}\)), \(K_{OL}\) = overall convective mass transfer coefficient for ammonia (m s\(^{-1}\)), \(A\) = area of emitting
surface (m\(^2\)), \([NH_3]_L\) = ammonia concentration at the lagoon liquid
surface (g m\(^{-3}\)), and \([NH_3]_a\) = ammonia concentration in air (g m\(^{-3}\))
(Ni, 1999). Two key input parameters required in Equation (1) are
the \(K_{OL}\) for NH3 and \([NH_3]_L\). In general, \([NH_3]_L\) is very small and is
neglected. Total ammonia nitrogen (TAN) is the sum of NH3 and
ammonium (NH4\(^+\)) concentrations. In aqueous solutions, equilib-rium exists between unionized NH3 and ionized NH4\(^+\). This equi-
librium is governed by NH4\(^+\) dissociation constant \((K_a)\) which is a
function of liquid temperature. The \(K_{OL}\) describes the NH3 transfer
rate from the liquid surface to the free air stream, while the \(K_a\) value
represents the volatile NH3 fraction of the TAN present in the bulk
liquid. The \(K_{OL}\) value for the liquid manure depends on several
factors, including the liquid TAN concentration, pH, liquid and
ambient air temperatures, solids concentration, and wind speed
(De Visscher et al., 2002; Arogo et al., 1999; Ni, 1999). Arogo et al.
(1999) modeled \(K_{OL}\) for an anaerobic under-floor swine manure
pit using data from a series of laboratory experiments conducted in
a convective emissions chamber and showed that air flow velocity
\((V_{air})\), lagoon-liquid temperature \((T_L)\), and air temperature \((T_{air})\)
fluctuated \(K_{OL}\). However, their model did not consider the contribu-
tion of the solids on the \(K_{OL}\), which other researchers have
indicated is a significant factor impacting NH3 volatilization rates
(De Visscher et al., 2002; Zhang et al., 1994).

Although studies focused on establishing empirical \(K_{OL}\) models
for livestock manure exist, primary emphasis has been placed on
swine lagoons and little attention has been given to dairy manure
storage systems (Ni, 1999). As an alternative, research has relied
more on theoretical approaches to determining mass transfer coefficients
for anaerobic dairy lagoons. For instance, Rumburg et al. (2008)
compared direct measurements of NH3 emissions with predictions
generated by a process-based model that used theoretical and empirical \(K_{OL}\) values reported from Ni (1999) for
dairy manure. The results of this study revealed that theoretically
derived \(K_{OL}\) values exhibited a significantly wider range of errors
(120% normalized mean error (NME)) compared with empirical
values (21% NME). Because theoretical \(K_{OL}\) derivations for livestock
wastewaters are inadequate and empirical \(K_{OL}\) values are largely
lacking for dairy wastewaters (Montes et al., 2009; Ni, 1999), an
empirical \(K_{OL}\) model for dairy manure is critically needed to
enhance NH3 emission models. The overall objective of this
research was to develop a statistical model using experimentally
derived NH3 mass transfer coefficients for dairy wastewater
and improve the reliability of NH3 emission process-based models
applications in liquid dairy manure systems.

2. Materials and methods

2.1. Theory behind \(K_{OL}\) determination

Ammonia release from anaerobic dairy lagoon wastewater
depends on the resistance of its transfer and the concentration
gradient between the lagoon liquid and the atmosphere (Arogo
et al., 1999) as indicated by Equation (1). Fig. 1 offers a conceptual
process of NH3 release from an anaerobic dairy lagoon.

Fig. 1 shows NH3 emissions from the bulk liquid manure into
the atmosphere is influenced by the Henry's constant \((k_H)\)
and convective mass transfer \((k_c)\) in gaseous phase. The \(K_{OL}\) for NH3 is
a function of \(k_H\) and \(k_c\). The effect of diffusion mass transfer \((k_d)\)
is negligible compared to \(K_{OL}\) and this term is usually disregarded
in most process models. In addition, the NH3 concentration in the
air is also insignificant compared with its concentration in the liquid,
especially for open-surface storages. Equation (1) can thus be re-
written as Equation (2), where \(t\) is the time step and the negative
sign indicates that NH3 concentration in the liquid matrix decreases
with time. Equation (2) can further be simplified to Equation (3)
by noting that \(M_{TAN} = V \times TAN\), where \(V = \) volume of manure (m\(^3\))
and \(TAN = \) the total ammoniacal nitrogen concentration (g m\(^{-3}\)).

\[
\frac{dM_{TAN}}{dt} = -K_{OL} A [NH_3]_L
\]  

(2)

\[
\frac{dTAN}{dt} = -K_{OL} A [NH_3]_L
\]  

(3)

Equation (3), however, cannot be solved because it is impossible
to measure the concentration of free NH3 in the wastewater.
Substituting \(a \times TAN\) for \([NH_3]_L\) in Equation (3) and integrating
translates into Equation (4), where \(a\) is the unionized (NH3) fraction
of TAN in the liquid manure, and \(TAN_{OL}\) and \(TAN_a\) are the initial
and current TAN concentrations in the bulk liquid manure at a given
time \(t\), respectively. At liquid pH values above 11.0, all of the TAN is
in the form of free NH3 and hence \(a = 1\) (see Fig. 2). The logarithmic

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**Fig. 1.** Ammonia release mechanism from liquid manure (Ni, 1999).
form of Equation (4), as shown in Equation (5), is a more preferable form because for $\alpha = 1$ and a known $A$ and $V$, $K_{OL}$ is computable from the slope of linear regression plot.

$$\text{TAN}_t = \text{TAN}_{O.L} \times e^{-\left(\frac{K_{OL}a}{V}\right)t}$$

(4)

$$\ln\left(\frac{\text{TAN}_t}{\text{TAN}_{O.L}}\right) = -K_{OL}a \frac{A}{V}t$$

(5)

2.2. Apparatus

A convective emission chamber was used to evaluate the impacts of relevant environmental parameters on NH$_3$ volatilization rates to establish an empirical $K_{OL}$ model. Fig. 3 is a photograph of the chamber, which is similar to units used in previous studies (Arogo et al., 1999; Shaw, 1994; Zhang, 1992). The convective emission chamber consisted of a blower, a flow-controller unit, two screens (3 mm stainless steel, 120 cm apart) to create turbulence, and a sample-chamber. The overall chamber dimensions were 4.2 m $\times$ 0.45 m $\times$ 0.15 m ($L \times W \times H$) and the test section dimensions were 1.2 m $\times$ 0.45 m $\times$ 0.15 m ($L \times W \times H$). The chamber walls were insulated and two thermocouples were used to control the $T_{air}$ within $\pm 1$ °C. The $V_{air}$ was controlled within $\pm 0.1$ m s$^{-1}$ using a damper at the inlet of the air generator. The sample test-pan (27.9 cm $L \times 17.8$ cm $W \times 3.5$ cm $H$) was placed in a constant temperature water bath to maintain set temperatures during the experiments. The water bath also maintained specified temperatures within $\pm 1$ °C.

2.3. Experimental design

The $K_{OL}$ values were determined under the following randomized conditions:

1. Air temperatures: 15, 25, and 35 °C;
2. Air velocities: 0.5, 1.0, 1.5, 2.5, and 4.0 m s$^{-1}$;
3. Manure liquid temperatures: 5, 15, 25 and 35 °C; and
4. Total solid concentrations: 0.5, 1.0, 1.5, 2.0, 2.5% (w/w basis); typical TS values for dairy lagoon liquid (Mukhtar et al., 2004).

Dairy manure (with concentration of TS of $\sim 3.0\%$ and 500 mg L$^{-1}$ TAN) was obtained from Washington State University Knott Dairy Research Center, Pullman, WA. The manure samples were diluted to the desired TS concentrations using tap water, and the pH was subsequently adjusted to 12.0 using 10 M NaOH to ensure that all TAN was in the form of free NH$_3$ (i.e., $\alpha = 1$ as shown in Fig. 2). The prepared manure sample was poured into the test pan, which was placed in the water-bath and allowed to attain the specified liquid-temperature. The temperature of the manure sample was checked frequently with a thermometer to ensure constant temperature conditions were maintained. The convective...
emission chamber was run for another 30 min to allow the manure sample to stabilize to the test conditions. Once the manure attained the desired test conditions, 1 mL samples were drawn 2 mm below the liquid surface at 5 locations in the test pan every 30 min for 4 h. To prevent further NH₃ loss, 5 mL of 2 M sulfuric acid was added to each collected sample. The samples were analyzed immediately after the experiment using the Hach Nessler colorimetric method 8033 adapted from standard methods 4500-NH₃ (APHA, 1992, 2005). Each test-condition was replicated 3 times.

The test-conditions examined in this study are shown in Table 1. These conditions represent expected dilute manure characteristics found in anaerobic dairy lagoons (and other similar storages) and environmental conditions typically encountered in the US Pacific Northwest.

### 3. Model development and data analysis

#### 3.1. Model development

Several modeling approaches for determining KOL values for livestock wastewaters and pure water are documented in literature (Liu et al., 2008; Guo and Roache, 2003; Argo et al., 1999; Haslam et al., 1924). Guo and Roache (2003) modeled KOL using six different organic compounds in laboratory convective emission chambers using the Sherwood number (dimensionless) approach as illustrated in Equations (6)–(9), where Sₘ is Sherwood number, also conceived considering all the factors included in obtaining the environmental conditions are presented in Table 2. For instance, Fig. 4.

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#### 3.2. Data analysis

Ammonia fluxes from the manure samples placed in the convective emission chamber for the respective environmental conditions were used to generate the empirical KOL data. The constants Cₖ, a, b, c, d and e in Equation (12) were obtained from regression analyses for NH₃ with their respective R² values at different environmental conditions examined in this study.

### 4. Results and discussion

#### 4.1. The KOL computations

The KOL values were calculated from the estimated slope of the non-linear regression plots of the exponential TAN concentration decay in the liquid dairy manure over the test period (240 min) according to Equation (5). The KOL values obtained from regression analyses for NH₃ with their respective R² values at different environmental conditions examined in this study are presented in Table 2. For instance, Fig. 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter value</th>
<th>KOL × 10⁻⁶, m s⁻¹</th>
<th>R²-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature, °C</td>
<td>15</td>
<td>2.65</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>2.16</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>1.81</td>
<td>0.99</td>
</tr>
<tr>
<td>Liquid temperature, °C</td>
<td>5</td>
<td>1.41</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>1.77</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>2.16</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>3.73</td>
<td>0.95</td>
</tr>
<tr>
<td>Air velocity, m s⁻¹</td>
<td>0.5</td>
<td>1.30</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1.59</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.17</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.10</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>3.13</td>
<td>0.97</td>
</tr>
<tr>
<td>TS concentration, %</td>
<td>0.5</td>
<td>3.03</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2.41</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.16</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>2.21</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>2.02</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>3.03</td>
<td>0.98</td>
</tr>
</tbody>
</table>
provides a representative test run conducted at $T_L = 25 \, ^\circ C$, $V_{air} = 1.5 \, m \, s^{-1}$, TS = 1.5%, and a pH of 12. The TAN concentration residual curve followed first-order reaction kinetics ($R^2 = 0.96$). The resultant $K_{OL}$ was calculated to be $2.1 \times 10^{-6} \, m \, s^{-1}$. This procedure of computing the $K_{OL}$ values was repeated for all the other test-conditions examined in this study to generate $K_{OL}$ data (Table 2) for modeling NH$_3$ $K_{OL}$ for dairy manure within the test-conditions.

In general, the TAN decay curves for liquid dairy manure were similar under constant TS concentrations, $T_{air}$, and $V_{air}$ at liquid manure temperatures ($T_L$) of 5, 15, 25, and 35 $^\circ C$ and followed the trend shown in Fig. 5. All the decay curves of the TAN concentration similarly followed first-order reaction rates with coefficients of determination ($R^2$) ranging from 0.95 to 0.99. A general tendency wherein $K_{OL}$ increased with increasing liquid manure temperature was observed. A similar trend was reported by Arogo et al. (1999) for $K_{OL}$ in swine manure. Ni (1999) reported $K_{OL}$ values ranged from $1.3 \times 10^{-6}$ to $11.7 \times 10^{-6} \, m \, s^{-1}$ for swine manure in a review of multiple studies. The results obtained from this study ($1.41 \times 10^{-6}$ to $3.73 \times 10^{-6} \, m \, s^{-1}$) fell within this broad span, but displayed a considerably narrower range.

4.2. Effect of liquid temperature ($T_L$) on $K_{OL}$

Fig. 6 presents the $K_{OL}$ values for NH$_3$ in liquid dairy manure at the four liquid temperatures (at fixed: air velocity of 1.5 $m \, s^{-1}$, TS concentrations 1.5%), and at air temperature of 25 $^\circ C$ examined in this study and the corresponding regression analysis showing the effect of $T_L$ on $K_{OL}$. In general, the $K_{OL}$ increased exponentially with an increase in the liquid temperature. Similar trends were observed for $K_{OL}$ values determined for swine manure in earlier studies (Arogo et al., 1999). In summary, as liquid temperature increases the free NH$_3$ fraction increases exponentially, and consequently the potential of NH$_3$ emission into the environment is enhanced. Consequently, ammonia emissions from the anaerobic dairy lagoons and other similar facilities are, generally, higher in warm seasons and during the day, and lower in colder seasons and at night (Todd et al., 2011; Blunden and Aneja, 2008; Aneja et al., 2001, 2000).

4.3. Effect of air velocity ($V_{air}$) on $K_{OL}$

The overall mass transfer coefficient for NH$_3$ as a function of air velocity ($V_{air}$) at $T_{air}$ of 25 $^\circ C$, $T_L$ of 25 $^\circ C$, and a TS concentration of 1.5% is shown in Fig. 7. Based on the linear regression plot ($R^2 = 0.92$), we infer that the $K_{OL}$ for liquid dairy manure is directly proportional to the air velocity above the liquid—air interface. This relationship is consistent with theoretical expectations, because higher wind velocities result in more rapid transfer of NH$_3$ away from the air space above the liquid—air interface. Transport of NH$_3$ away from the air above the liquid—air interface reduces NH$_3$ partial pressure and leads to enhanced volatilization. In essence, a greater NH$_3$ concentration gradient results; a governing factor for NH$_3$ loss in Equation (1). This implies that manure storage facilities located in areas exposed to stronger winds will experience elevated NH$_3$ emissions (Misselbrook et al., 2005; Arogo et al., 1999).

4.4. Effect of air temperature ($T_{air}$) on $K_{OL}$

The relationship between $K_{OL}$ and air temperature at $T_L = 25 \, ^\circ C$, $V_{air} = 1.5 \, m \, s^{-1}$, and TS = 1.5%, is shown in Fig. 8. The high

![Fig. 4](image-url) TAN decay residuals curve for dairy manure at $T_L = 25 \, ^\circ C$, $T_{air} = 25 \, ^\circ C$, $V_{air} = 1.5 \, m \, s^{-1}$, TS = 1.5%, and pH 12.

![Fig. 5](image-url) Ammonia decay curves over a period of 4 h at 12 pH, air velocity 1.5 $m \, s^{-1}$, TS concentrations 1.5%, and at liquid temperature 25 $^\circ C$.

![Fig. 6](image-url) $K_{OL}$ as a function of liquid temperature at $T_{air} = 25 \, ^\circ C$, $V_{air} = 1.5 \, m \, s^{-1}$, TS = 1.5% (error bars indicate standard deviations from means based on triplicate tests).

![Fig. 7](image-url) Relationship between $K_{OL}$ and air velocity at $T_L = 25 \, ^\circ C$, $T_{air} = 25 \, ^\circ C$, TS = 1.5% (error bars indicate standard deviations from means based on triplicate tests).
correlation of determination ($R^2$) of 0.99 indicates that $K_{OL}$ decreases with an increase in air temperature. This finding reflects the increase of dynamic viscosity ($\mu$) of air with an increase in ambient temperature. This phenomenon in turn increases resistance to NH$_3$ volatilization from the emitting surface. However, while higher air temperatures offer more resistance to NH$_3$ air pollution when considered alone, a corresponding increase in liquid temperature will result which promotes NH$_3$ emissions. Results of this study indicate a 1.4-fold increase in $K_{OL}$ for every 10°C rise in $T_L$ and a 1.2-fold decrease for every 10°C rise in $T_{air}$. This finding suggests that NH$_3$ volatilization rates from dairy manure are impacted more by the liquid temperature if both $T_L$ and $T_{air}$ increase by the same magnitude.

4.5. Effect of total solids concentration (TS) on $K_{OL}$

The effect of TS concentration at $T_L = 25$ °C, $T_{air} = 25$ °C, and $V_{air} = 1.5$ m s$^{-1}$, on $K_{OL}$ for dairy manure is presented in Fig. 9. The fitted exponential decay plot seems to adequately fit the experimental data ($R^2 = 0.81$). Consequently, while the $K_{OL}$ values for the liquid dairy manure decreased with increase in the TS concentration, in general, the effects at lower TS concentrations are greater than at higher TS concentrations. In previous research, Arogo et al. (1999) observed no significant effect of the TS concentration on the $K_{OL}$ from liquid swine manure when the TS concentration was lower than 10%. This study, however, indicates suspended solids in liquid dairy manure can impede NH$_3$ volatilization, which conforms to the assertions made by De Visscher et al. (2002). The latter researchers indicated that NH$_3$ adsorption on suspended organic solids reduced the diffusion coefficient resulting in lower NH$_3$ loss.

![Fig. 9. Effect of total solids on $K_{OL}$ at $T_L = 25$ °C, $T_{air} = 25$ °C, and $V_{air} = 1.5$ m s$^{-1}$ (error bars indicate standard deviations from means based on triplicate tests).](image)

**4.6. Our overall mass transfer model**

The $K_{OL}$ data (see Table 2) for dairy manure obtained from this laboratory study, with respect to variables $T_L$, $V_{air}$, TS, and $T_{air}$, were used in Proc NLIN SAS program to solve for the values of constants $a$, $b$, $c$, $d$ and $C_{OL}$ in Equation (12). The respective constants obtained from Proc NLIN are displayed in Equation (13). The strong coefficient of determination of this model ($R^2 = 0.83$) indicates consistency with the experimental data, providing a reliable tool for determining NH$_3$ $K_{OL}$ values for liquid dairy manure slurries, provided manure characteristics and environmental conditions are within the ranges evaluated in this study.

$$K_{OL} = 4.85 \times 10^{-11} \left(\frac{T_L}{1.5}\right)^{0.97} \left(\frac{V_{air}}{1.5ms^{-1}}\right)^{0.34} \left(\frac{T_{air}}{1.5ms^{-1}}\right)^{0.26} \left(\frac{TS}{1.5%}\right)^{1.5%}$$

Fig. 10 displays a plot comparing measured and model predicted $K_{OL}$ values of NH$_3$ for liquid dairy manure. The results indicate good agreement between the measured and the predicted $K_{OL}$ values with a normalized mean error (NME) of 9.6% which was calculated using Equation (14):

$$NME = \frac{\sum|X_{mod} - X_{mea}|}{\sum|X_{mea}|} \times 100%$$

where $n$ is the number of data values, while $X_{mod}$ and $X_{mea}$ are the modeled and measured $K_{OL}$, respectively.

4.7. Sensitivity analysis

Sensitivity analysis was performed by increasing respective variables by 10% within the range of experiment conditions. Sensitivity analysis showed $K_{OL}$ exhibited sensitivity to the factors considered in descending order: $T_L$, $T_{air}$, $V_{air}$ and TS concentration (Table 3). To test the combined sensitivity of these parameters on

![Fig. 10. Comparison of the actual and the predicted $K_{OL}$ values in dairy manure slurries.](image)

**Table 3 Sensitivity analysis of the predicted fluxes by the model.**

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>10% Change within parameter range $^a$</th>
<th>$K_{OL}$ sensitivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_L$ °C</td>
<td>2.5</td>
<td>7.9</td>
</tr>
<tr>
<td>$V_{air}$ m s$^{-1}$</td>
<td>0.15</td>
<td>3.2</td>
</tr>
<tr>
<td>$T_{air}$ °C</td>
<td>2.5</td>
<td>-5.9</td>
</tr>
<tr>
<td>TS %</td>
<td>0.15</td>
<td>-2.5</td>
</tr>
</tbody>
</table>

$T_L$ = Lagoon-liquid temperature; $T_{air}$ = Air temperature; $V_{air}$ = Air velocity; TS = Total solids concentration w/w.

$^a$ Standard parameter range: $T_L = 25$ °C, $T_{air} = 25$ °C, $V_{air} = 25$ °C, TS content = 1.5%.
of NH₃ all variable were increased simultaneously by 10%, which resulted in KOL increasing by 2.2%. This analysis indicates that T and Vair exert a greater impact on NH₃ emissions from dairy lagoons than Tail and TS when all parameters increase simultaneously by the same percentage.

5. Summary and conclusions

The overall mass transfer coefficient of NH₃ for bulk liquid dairy manure to the air was empirically modeled using data from a series of experiments performed in a laboratory convective emission chamber. The following conclusions were drawn from the experimental results and the associated modeling process:

1. KOL values increased with an increase in liquid temperature and an increase in air velocity, but decreased with an increase in air temperature under the conditions tested. These findings correspond with expected results and agree with similar studies that have examined NH₃ emissions from other types of livestock liquid manure management systems.

2. The KOL decreased with an increase in TS concentration in the range of 0.5–2.5%, which suggests that solids impede the mass transfer of NH₃ from liquid dairy manure. Other researchers have reported conflicting findings in regards to the impact of TS on KOL values. However, the relationship between KOL and TS appeared to resemble a second-order reaction, but they better fitted with first-order kinetics and the difference between KOL values was most pronounced between 0.5 and 1.0% TS.

3. The developed model for predicting the KOL of NH₃ from liquid dairy manure exhibited an NME of 9.6%, which demonstrates a good fit with the experimental data.

4. KOL exhibited sensitivity to the four model parameters considered in descending order: liquid manure temperature, ambient air temperature, wind or air velocity, and total solids concentration.

The suite of NH₃ mass transfer coefficients determined in this study provides measured values applicable to liquid dairy manure handling systems, and fills a gap in knowledge for this livestock sector. Moreover, the establishment of an empirical model that yields accurate KOL estimates under a range of conditions provides a functional tool for use in process-based models used to predict NH₃ emissions. These findings will help improve our understanding of NH₃ volatilization from dairy operations and help develop approaches to mitigate emissions to the environment.

Acknowledgments

The authors would like to thank the Agricultural Research Center, Washington State University for the financial support. The authors would also like to thank Dr. Brenton Sharratt, USDA – ARS Scientist and Research Leader, Land Management & Water Conservation Research Unit Pullman, Washington, for his invaluable suggestions on the design of the Convective Emission Chamber, and Dr. Simon Smith for his editorial help.

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