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Wind tunnel study of ammonia transfer from a manure pit fitted with a dairy cattle slatted floor

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In dairy cattle systems, most of the feces and urine go to the pit. At the manure pit level, mass transfer of NH\textsubscript{3} (\(k_{NH3}\)) has many factors, but practical difficulties hamper a controlled field evaluation. In this study, we propose a methodology for the determination of an alternative, more practical, pit transfer coefficient of NH\textsubscript{3} (PTC), and compare it with \(k_{NH3}\) determined from other scientific studies. The aims of this research study were: (1) to develop a wind tunnel set-up which mimics air flow patterns between the slats and above a clean section of a slatted floor section, featuring an aqueous NH\textsubscript{3}-emitting solution; and (2) to assess how air velocity, turbulence intensity, NH\textsubscript{3} concentration ([NH\textsubscript{3}]) and PTC are influenced by inlet airflow ventilation rate (VR) forced deflection of the air above the slats into the manure pit through varying the deflection angle (DA) of a deflection panel and varying pit headspace height (HH). Main conclusions were: (1) the calculated PTC values presented a good fit to the power function of the air speed near the slats (\(u\)) (\(p < .001\)) while the average PTC (0.0039 m s\(^{-1}\)) was comparable to \(k_{NH3}\) values obtained from other studies, by remaining within the range of average values of 0.0015–0.0043 m s\(^{-1}\); (2) VR and DA significantly impacted [NH\textsubscript{3}] profiles and PTC (\(p < .001\)) and (3) changing slurry pit from 0.10 to 0.90 m HH did not significantly impact [NH\textsubscript{3}] or PTC (\(p = .756\) and \(p = .854\), respectively).

\textbf{Keywords:} ammonia-emitting solution; pit headspace height; barn ventilation rate; automatic solution pH control; flow patterns

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Introduction

The gas ammonia (NH₃) is a major cause of indoor air pollution in livestock systems, affecting animal and human health [1] and once released into the environment, it contributes to eutrophication and acidification of ecosystems.[2–5] Hence, as from 2001, European Union’s National Emission Ceiling (NEC) Directive imposed the maximum allowed NH₃ emission levels to be reached by each country member. Since then, many research studies have been developed with the attempt to test mitigation strategies in order to abate NH₃ emissions from production systems of the main livestock categories, including cattle barns.

Cattle farms are known for producing large amounts of excrements and for significantly emitting NH₃ when compared to other livestock categories.[6–8] The majority of cattle houses in Belgium and Northern Europe feature slatted floors on top of a manure pit. In these systems, a considerable percentage of the total excreted nitrogen is transformed still on top of the slatted floor, namely into NH₃ through an enzymatic reaction of urease (abundantly present in feces) on urea (in the urine).[9] Nevertheless, most of the excrements pass through the slats into the pit, where under certain conditions NH₃ is released to the air through enzymatic degradation and bacteriological decomposition.[10–13]

The transfer of NH₃ from the slatted floor surface in livestock systems has been widely studied,[14–19] while the factors related to NH₃ transfer from the pit are not yet fully understood. There are many practical difficulties concerning field determination of the contribution of the manure pit to total emissions. For instance, the harsh environmental conditions under the floor make it a challenging place to monitor. Attempting to reproduce and study emissions from the manure pit in laboratory conditions may be advantageous.

The NH₃ mass transfer coefficient (kNH₃) is inversely proportional to the concentration gradient (Δ[NH₃] = [NH₃]i − [NH₃]∞), which is defined by the difference between the concentration measured at the fluid interface ([NH₃]i) at and at a certain distance from the source ([NH₃]∞).[20] While making measurements of [NH₃]i, in the lab is feasible with free emitting surfaces, the presence of the slats in practical situations might make it a cumbersome task. Still, the determination of a manure pit transfer coefficient (PTC) with the same logistic model used to estimate kNH₃, but considering [NH₃]i as the NH₃ concentration measured between the slats, may lead to valuable information to characterize emissions from full-scale barns, if PTC values compared well to kNH₃.

It is well known that NH₃ volatilization from manure is dependent on variables such as nitrogen content, temperature (T), pH and air flow properties near the emitting surface.[15,21,22] The latter are of crucial importance in triggering the NH₃ release process,[17] because they allow for the convective transport of freshly volatilized molecules upwards the manure pit and the barn, a mechanism that repeats itself for as long as the conditions are favourable.[23–26]

Ye et al. [27] and Ye et al. [28] reported laboratory studies carried out to evaluate the effect of air velocity (u), turbulence intensity (TI), pH, slats opening size and headspace height (HH) on NH₃ emissions from a scale pig house model with an aqueous solution mimicking the manure. In a later study, Ye et al. [29] monitored several climate and design variables along with NH₃ emissions from pigs housed in a full-size experimental room. Those authors found that the factors that explained most of the variability of NH₃ emissions from the pigs were ventilation rate (VR), floor system, manure temperature, HH and the presence of a manure pit curtain. Although these reduced and full-size scale studies explained influencing factors on NH₃ emission rates from pig houses, their outcomes might not be transferable to dairy cattle housing systems with slatted floor, due to the obvious inherent differences between systems such as animal category and thus manure properties, barn design and the overall system management.

Dairy cattle houses are mostly naturally ventilated, [7,30] and modern design systems account for relatively large side openings which allow for high air exchange rates that will likely lead to higher air velocities near the slats, potentially having a stronger impact on the flow properties in the manure pit headspace than in mechanically ventilated barns. Due to regulations set by European and national laws in Belgium, [31] field applications of manure are only allowed between February and October, meaning that for half of the year the manure usually has to remain in the pit, which will cause it to be nearly at maximum capacity for a couple of months. The headspace volume of the manure pit has been found to influence kNH₃, because at lower HH values, the boundary layer [32] at the manure liquid surface is more likely to be affected by the flow patterns near the slats. However, a controlled study including the combined effect of ventilation patterns, that is, air velocity (u) and TI near the slats with effects of HH that are applicable to dairy cattle systems is meager in the current literature.

Therefore, the aim of this study was to develop a wind tunnel set-up which mimics airflow patterns between the openings and in the first centimeters above a clean section of a slatted floor typically found in dairy cattle barns, equipped with an aqueous NH₃-emitting surface that resembles manure pit conditions. Specific objectives were: (a) to assess how u, TI and [NH₃] are influenced by different VR values, by deflecting the air flow in the first centimeters above the slats and by varying HH and (b) to calculate PTC values from the wind tunnel set-up and compare it to kNH₃ values from other studies, and assess PTC dependence on changing VR, deflection angle (DA) and HH.
Materials and methods

In order to achieve the objectives of the study, one section of a slatted floor typically found in dairy cow barns was placed in the test section of a wind tunnel specially built for this purpose. Under the slatted floor, the manure pit was installed along its edges, closing all gaps near the pit walls.

In order to divert the air flow entering the test section, a deflector panel was additionally installed inside the wind tunnel at 0.43 m from the inlet side of the test section, that is, above the first set of floor slits. The deflector consisted of a 0.005 m thick polycarbonate shield spanning the wind tunnel cross-sectional area. A rotating axis placed at the top of the deflector allowed for manual positioning at any angle between 0° and 90°. The setting of 0° resulted in no change in airflow direction, since this was the horizontal position of the deflector, while 90° implied a complete downward airflow deviation towards the frontal set of floor slits.

The stainless steel container in the pit was filled with 0.225 m³ of a standard 10⁸ mg m⁻³ ammonium chloride (NH₄Cl) solution, prepared by dissolving NH₄Cl in tap water, yielding a total ammonia nitrogen (TAN) concentration of 33.7 mg m⁻³. This relatively high concentration was chosen to avoid the depletion of the NH₃-emitting source during the course of the experiments.

To allow for a stable level of NH₃ volatilization from the liquid phase, the pH of the solution was controlled by constant circulation of NH₄Cl solution from and to the container, at a rate of approximately 5 × 10⁻⁴ m³ s⁻¹, through a custom-built pumping system. The NH₄Cl solution pH was maintained at a set-point of 8.00 by dosing with the buffer solution, which yielded an NH₃/NH₄⁺ ratio of 20%.[33] The buffer solution consisted of a 1:1 solution of Na₂CO₃ and NaHCO₃, leading to a buffer concentration of 184 mg m⁻³, which was stored in a separate container. The pH of the NH₄Cl solution was monitored with an electrode-type sensor (model HI 1006–32, Hanna Instruments, 0.1 Hz measuring frequency, 0.01 precision) fitted to the circulation system. When the pH of the NH₄Cl solution dropped below the set-point value, a solenoid valve (type pH 500, Hanna Instruments, Temse, Belgium) dosed buffer solution into the circulatory system in order to keep the pH constant (Figure 2). The temperature of the NH₄Cl solution (Tsol) was measured with a resistance temperature sensor (RTD type, Jumo GmbH & Co.

Description of the wind tunnel with manure pit model and NH₃ release control set-up

An 8.00 m Long × 1.15 m Wide × 0.50 m High (L × W × H) wind tunnel was constructed inside an environmentally semi-controlled laboratory (central ventilation and heating system for control of temperature and VR, Figure 1). The wind tunnel consisted of a stainless steel frame, with concrete floor and walls, and windows of Plexiglas®. Negative pressure conditions were created inside the wind tunnel with a suction fan (Fancom BV, model IF35, Pan-ningen, the Netherlands) placed at the outlet side. The fan air flow rate was controlled and varied between 0 and 1350 m³ h⁻¹, resulting in inlet air velocities (ухал) in the range of 0–0.65 m s⁻¹. The test section of the wind tunnel was located 2.5 m from both extremities, and had dimensions of 3.00 m L × 1.00 m W × 0.500 m H. The floor of the test section consisted of full-scale concrete slats, typically applied in dairy cow barns, with dimensions of 3.00 m L × 1.00 m W × 0.18 m Depth (D), containing a total of 30 slits, each measuring 0.49 m L × 0.04 m W, thus yielding an opening porosity of 20%. The space under the slats had dimensions of 2.66 m L × 1 m W × 1.38 m D. The manure pit had a custom-built stainless steel container (2.65 m L × 1.00 m W × 0.19 m H) mounted on a hydraulic lift table (BD Lift & Container International AB, Klippan, Sweden), which allowed for different pit HH ranging from 0.10 to 0.90 m. To ensure air tightness around the container, an inflatable tube was installed along its edges, closing all gaps near the pit walls.

In order to divert the air flow entering the test section, a deflector panel was additionally installed inside the wind tunnel at 0.43 m from the inlet side of the test section, that is, above the first set of floor slits. The deflector consisted of a 0.005 m thick polycarbonate shield spanning the wind tunnel cross-sectional area. A rotating axis placed at the top of the deflector allowed for manual positioning at any angle between 0° and 90°. The setting of 0° resulted in no change in airflow direction, since this was the horizontal position of the deflector, while 90° implied a complete downward airflow deviation towards the frontal set of floor slits.

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Figure 1. Representation of the wind tunnel set-up. 1, inlet; 2, wind deflector panel; 3, slatted floor; 4, buffered NH₄Cl solution container; 5, headspace volume; 6, exhaust.
Figure 2. Snapshot of aqueous solution pH 15 hours prior to the start-up of an experimental section. The peaks above 8.1 denote momentary dosage events with buffer solution.

KG, Fulda, Germany, 0.017 Hz sampling frequency, 0.1°C precision). Aqueous solution pH and $T_{sol}$ were recorded by a data logger (Squirrel type 2040, Grant Instruments, Cambridge, UK).

**Monitored variables and system check-up procedures**

The monitoring of $u$ was performed with unidirectional hot-film anemometers (Model EE66, E+E Elektronik, Engerwitsdorf, Germany, 0.017 Hz sampling frequency, 0.01 m s$^{-1}$ precision) at two different heights. Between slats and above slats in the middle height of the wind tunnel (0.25 m), at two positions (1 m apart from each other) along the length of the wind tunnel experimental section, totaling four different points in space. One additional anemometer was installed upstream the deflector panel, at 0.25 m from the slats for monitoring the undisturbed inlet air velocity ($u_{inlet}$, Figure 3).

At each position where air velocity measurements were taken, $T_I$ values were calculated with Equation (1):

$$T_I = \frac{SD_u}{u_{avg}},$$

where $T_I$ is the turbulence intensity (dimensionless); $SD_u$ is the standard deviation of the air velocity measured at a certain point over the time length of measurements (90 min, m s$^{-1}$) and $u_{avg}$ is the mean air velocity at a certain point over the time length of measurements (90 min, m s$^{-1}$).

Concentrations of NH$_3$ were monitored with a photoacoustic analyzer (model INNOVA 1314, AirTech Instruments, Ballerup, Denmark, 0.1 mg m$^{-3}$ precision) equipped with a multiplexer to collect air samples at two heights (between and 0.25 m above slats, Figure 3) and at

![Figure 3. Longitudinal cross-section representation of the experimental wind tunnel (not to scale) at the middle distance from the lengthwise sides, indicating the positions of the anemometers (♦ and • are for velocity measurements made at the inlet and inside the test section of the wind tunnel, respectively) and NH$_3$ concentration sensors (▲).](image)
three distances across the length of the measuring section of the wind tunnel (1 m apart from one another), leeward from the deflector panel. This sampling scheme yielded six measurements per cycle, plus one for background concentration measurements at the wind tunnel inlet. Samples of air from each point were consecutively taken at 5 min intervals, with the first 3 min for stabilization and the last 2 min for measurement, yielding a measurement cycle of 35 min for one complete loop. The air coming from each sampling port was channelled into the photoacoustic analyzer with fluoroethylene tubing (6.3 mm inside diameter). The successive sampling was accomplished through controlled operation of seven solenoid valves (CBISS Intelligent Sampling System MK2, Ballerup, Denmark).

All instruments used in this study were factory calibrated within 6 months prior to the beginning of the trials.

In order to certify that the wind tunnel system and the monitoring equipment were functioning properly and consistently over the course of the experiments, standard conditions for inlet VR of 0.262 m$^3$ s$^{-1}$ (equivalent to an inlet air velocity of 0.46 m s$^{-1}$), HH of 0.5 m and deflector panel angle (DA) of 0° were applied for a period of at least 48 hours prior to the start of the experiments. This procedure was repeated on a daily basis (between 6.00 pm and 9.00 am), and the total execution time of the experiments in this study was 2 weeks.

**Experiments on varying inlet air VR, HH and DA**

Two experiments were performed, one in which different levels of VR and DA were combined and tested, and another one where different levels of HH and DA were evaluated. In the first experiment, four different VR (0.150, 0.225, 0.300 and 0.375 m$^3$ s$^{-1}$) were applied to the exhaust fan of the wind tunnel, which resulted in $u_{\text{inlet}}$ values of 0.26, 0.39, 0.52 and 0.65 m s$^{-1}$, respectively. At each studied VR, five different airflow DA were imposed through manipulation of the deflector panel inside the wind tunnel: 0° (completely open), 20°, 45°, 70° and 90° (completely closed). During this experimental series, an intermediate HH of 0.50 m was maintained.

In the second experiment, different levels of HH were achieved by altering the height between the bottom of the slatted floor and the container that held the NH$_3$-emitting solution. The tested HH values were 0.10, 0.37, 0.63 and 0.90 m, which reflected different full-scale manure levels, which can occur in practice due to manure production. At each HH, five different DA were imposed through the manipulation of the deflector panel inside the wind tunnel: 0°, 20°, 45°, 70° and 90°. A constant inlet VR of 0.263 m$^3$ s$^{-1}$ was used, resulting in a $u_{\text{inlet}}$ of 0.46 m s$^{-1}$.

In each experiment, the combination of 4 levels of VR or HH with 5 levels of DA yielded a total of 20 trials, each lasting 70 min, and performed at random. All 40 trials were performed within a 2 weeks period.

**Calculation algorithm for PTC**

In livestock manure, the ion ammonium (NH$_4^+$), which is the precursor of liquid NH$_3$ (NH$_3$L), is the direct byproduct of mineralization of proteins and/or enzymatic degradation of urea. In our experiments, the ion NH$_4^+$ was supplied by the NH$_4$Cl solution. The conversion of NH$_4^+$ into NH$_3$L is described as a reversible chemical reaction and is a function of the dissociation constant ($K_D$, Equation (2)). Higher pH values shift the equilibrium of Equation (2) to the right, and more NH$_3$L will be available for volatilization. The volatilization of NH$_3$L into gaseous NH$_3$ (NH$_3$,G), is a function of the Henry ($K_H$) constant (Equation (3)).

\[
\text{[NH}_4^+\text{]} \leftrightarrow \text{[NH}_3\text{L}] + \text{[H}^+\text{]},
\]

(2)

\[
\text{[NH}_3\text{L}] \leftrightarrow \text{[NH}_3\text{,G]},
\]

(3)

where [NH$_4^+$] is the concentration of the ion NH$_4^+$ at the emitting solution surface (mg m$^{-3}$); [NH$_3$L] and [NH$_3$,G] are the liquid and gaseous concentrations of NH$_3$, respectively, at the emitting solution surface (mg m$^{-3}$); [H$^+$] is the proton concentration at the surface of the aqueous solution and ([H$^+$] = $10^{-pH}$ = $10^{-8}$ mg m$^{-3}$ at a pH of 8.00).

The constants $K_D$ and $K_H$ are the dissociation and Henry constants (dimensionless), respectively. They can be calculated using Equations (4) [34] and 5 [35], respectively:

\[
K_D = 10^{-(0.0897+(2729/T))},
\]

(4)

\[
K_H = 10^{+1.69+(1477.7/T)},
\]

(5)

where $T$ is the emitting solution surface temperature (K).

Since it is not possible to measure [NH$_3$,L] directly, it was estimated as a function of [TAN], [H$^+$] and $K_D$, as presented in Equation (6):

\[
[\text{NH}_3\text{,L}] = [\text{TAN}]/(1 + ([\text{H}^+] K_D))
\]

(6)

where [TAN] is the total ammonia nitrogen concentration at the emitting solution surface (10$^3$ mg m$^{-2}$).

The relationship between [NH$_3$,L] and [NH$_3$,G] is given by Equation (7):

\[
[\text{NH}_3\text{,G}] = [\text{NH}_3\text{,L}] / K_H.
\]

(7)

In this study, PTC was calculated using Equation (8):

\[
PTC = (VR_{\text{STD}} \times [\text{NH}_3]) / ([A_s] \times [\text{NH}_3\text{,G}]),
\]

(8)

where PTC is the pit mass transfer coefficient of NH$_3$ (m s$^{-1}$); $VR_{\text{STD}}$ is the ventilation rate corrected for standard pressure (1 atmosphere) and temperature (25°C) (m$^3$ s$^{-1}$); [NH$_3$] is the mean concentration of NH$_3$ measured between and above the slats (mg m$^{-3}$); and $A_s$ is the emitting solution surface area (2.40 m$^2$).

Values of PTC from this study were compared with $k_{\text{NH}_3}$ values calculated from the models presented in other studies (Table 1).
Data processing and statistical analyses
With the data collected for system check-up tests, the values of the following variables were averaged over periods of at least 15 h: NH₄Cl solution pH and temperature ($T_{sol}$, °C), along with air velocity at the inlet ($u_{inlet}$, m s⁻¹) and inlet air temperature ($T_{inlet}$, °C) measured inside the wind tunnel, 0.25 m above the slats. During this period, the conditions remained approximately constant. One sample two-sided t-test was performed on $pH$ and $u_{inlet}$, in order to test the hypothesis that mean values were not significantly different from the expected values of 8.00 and 0.46 m s⁻¹, respectively. One sample two-sided t-test was also applied on the variables $T_{sol}$ and $T_{inlet}$ in order to test the hypothesis that individual values measured every 15 h period were not significantly different from the mean value over all periods. The t-test analyses were performed with the procedure *t* test in SAS® (Version 9.4, Cary, North Carolina, USA).

During experiments, data collected on the dependent variables [NH₃] and $u$ at every trial were averaged over the measurement period (70 min). Then calculations of $TI$ were performed with $u$ data by using Equation (1).

In order to determine the influence of the factors $VR$, $DA$ and $HH$ on the dependent variables [NH₃], $u$ and $TI$, linear regression analysis was performed. It was expected that, for a specific variable, the sampling positions between slats versus 0.25 m above the slats would significantly impact [NH₃], $u$ and $TI$. Distinct regression models were obtained for the explained variables at the slats level and at 0.25 m above slats. For each dependent variable, two different models were developed, one combining $HH$ and $DA$ and another one with $VR$ and $DA$. The analysis was done with the procedure generalized linear mixed models (*procglm*) in SAS® to test whether the combined effects of the continuous $VR$ and $DA$ or $HH$ and $DA$, along with their interactions, could be explained by the respective fixed effects model described in Equations (9) or (10):

$$Y_{ij} = \alpha + \beta_1 \cdot VR_i + \beta_2 \cdot DA_j + \beta_3 \cdot (VR_i \times DA_j) + \epsilon_{ij},$$

or

$$Y_{ij} = \alpha + \beta_1 \cdot HH_i + \beta_2 \cdot DA_j + \beta_3 \cdot (HH_i \times DA_j) + \epsilon_{ij},$$

where $Y_{ij}$ is the measured [NH₃], $u$ or $TI$; $VR$ is the effect of the ventilation rate (0.150, 0.225, 0.300 and 0.375 m³ s⁻¹) on [NH₃], $u$ or $TI$, here considered a continuous variable; $HH_i$ is the effect of the pit headspace height (0.10, 0.37, 0.63 and 0.90 m) on [NH₃], $u$ or $TI$, here considered a continuous variable; $DA_j$ is the effect of the deflection panel angle (0°, 20°, 45°, 70° and 90°) on [NH₃], $u$ or $TI$, here considered a continuous variable; $\beta_1$, $\beta_2$ and $\beta_3$ are regression coefficients obtained from the analysis; $\alpha$ is the intercept, obtained from the analysis and $\epsilon_{ij}$ is the independent normally distributed homogenous random error.

In order to allow the comparison with $k_{NH3}$ from the studies mentioned in Table 1, non-linear regression was performed with the *PTC* data calculated in this study against $u$ according to the model in Equation (11). The shape of Equation (11) was chosen because according to theory, the mass transfer coefficient is expected to vary with $u$ according to a power function. [20] This analysis was performed with the procedure *procglm* in SAS®.

$$PTC = a \times u^b,$$

where $PTC$ is the transfer coefficient of NH₃ from the pit (m s⁻¹); $u$ is the local air velocity (m s⁻¹) measured between slats and $a$ and $b$ are regression coefficients obtained from the analysis.

All statistical analyses in this paper were performed for a significance level of 0.05, and the fit of the models
was evaluated by an examination of the normal probability plots of the residuals and by inspection of the residuals plotted against the predicted values.

Results and discussion

Performance of the system

The results of the statistical analysis performed on the variables monitored during the check-up tests prior to the start of the experiments and throughout the experimental period are summarized in Table 2. The overall measured pH of the aqueous solution was 8.02 ± 0.03, which was not significantly different from the set-point value of 8.00 (p = .086). This outcome suggests that the automatic pH buffering system was working properly and consistently during the experiments. The average value for the variable \( \mu_{\text{inlet}} \) monitored under standard conditions (\( VR = 0.262 \text{ m}^3\text{ s}^{-1}, HH = 0.5 \text{ m and } DA = 0^\circ \)) was 0.47 ± 0.01 m s\(^{-1}\), and was not significantly different from the expected value of 0.46 m s\(^{-1}\) (p = .089), indicating that the velocity given by the hot-wire anemometer agreed with the expected velocity of the exhaust fan. This outcome also indicates that, in averaged terms, the drag effect due to the presence of the sensors and sampling ports did not allow for a significant pressure drop inside the test section of the wind tunnel that could affect average air velocities. Hence, this drag effect of the presence of sensors and sampling ports was considered negligible. In fact, a Computational Fluid Dynamic (CFD) study performed in order to allow detailed visualization of the flow patterns inside the test section of the wind tunnel (data not presented) indicated that the modelled air velocities at the same locations where the sensors and sampling ports were placed agreed well with the air velocities measured experimentally.[40]

Concerning the variable \( T_{\text{inlet}} \), the t-test results indicated that some of the measurements did statistically differ from the overall mean (\( p = .001 \)); however, temperature values spanned between 16.0°C and 18.3°C, which is considered a relatively small range for the purposes of this research study, meaning that this significant effect is not relevant. A similar outcome was observed for \( T_{\text{sol}} \), with a mean value of 16.6 ± 0.4°C, but with the measured maximum and minimum values differing by only 0.9°C.

In general, it was observed that the variability of the monitored variables during the check-up tests was relatively small, indicating that the ventilation system of the wind tunnel and the conditions of the aqueous solution presented good stability and repeatability during the trials.

Effects of varying inlet VR and DA

The equations resulting from the regression analysis on the effects of \( VR \) and \( DA \) on \( u \), \( TI \) and \([NH_3]\) are presented in Table 3, while the mean values are graphically shown in Figure 4. The results indicate that \( u \) significantly increased with increasing \( DA \) (\( p = .001 \)) at the slats level, and significantly decreased with \( DA \) (\( p = .001 \)) at 0.25 m from slats. This outcome was expected, because as the deflection panel was lowered (increasing \( DA \)), the flow at 0.25 m was obstructed, resulting in lower average air velocities, while forcing the air to move through the decreasing size opening between the deflection panel and the slats, yielding higher average air velocities near the slats. Concerning the variable \( VR \), the statistical analysis indicated that \( u \) was positively impacted by \( VR \) at both heights.

| Variable | Expected value | Measured value (mean ± SE) | Min. value | Max. value | \( n \) | \( p \)-value\( ^b \) |
|----------|----------------|-----------------------------|------------|------------|------|------------------|
| \( pH \)  | 8.00           | 8.02 ± 0.03                 | 8.00       | 8.09       | 8    | 0.086            |
| \( \mu_{\text{inlet}} \) (m s\(^{-1}\)) | 0.46           | 0.47 ± 0.01                 | 0.44       | 0.48       | 8    | 0.089            |
| \( T_{\text{inlet}} \) (°C) | –              | 17.0 ± 0.3                  | 16.0       | 18.3       | 8    | 0.001            |
| \( T_{\text{sol}} \) (°C) | –              | 16.6 ± 0.4                  | 16.1       | 17.0       | 8    | 0.001            |

\( ^a \) Number of observations.

\( ^b \) \( p \)-Values smaller than .050 were considered significant in this study.

| Variable | Regression model |
|----------|------------------|
| \( u \)  | \( u = (0.23 ± 0.12) \cdot VR + (0.0034 ± 0.0006) \cdot DA \) |
| \( u \)  | \( u = (2.2 ± 0.2) \cdot VR + (−0.003 ± 0.001) \cdot DA \) |
| \( TI \) | \( TI = (1.4 ± 0.3) \cdot VR + (0.006 ± 0.003) \cdot DA - (0.03 ± 0.01) \cdot VR \times DA \) |
| \( TI \) | \( TI = (0.97 ± 0.02) \cdot VR + (0.0003 ± 0.0001) \cdot DA \) |
| \([NH_3]\) | \( [NH_3] = (52 ± 6) + (−0.37 ± 0.11) \cdot DA \) |
| \([NH_3]\) | \( [NH_3] = (7 ± 3) + (0.14 ± 0.05) \cdot DA \) |
Figure 4. Air velocity ($u$, m s$^{-1}$; a and b), $TI$ (dimensionless; c and d) and NH$_3$ concentration ([NH$_3$], mg m$^{-3}$; e and f) plotted against $VR$ (m$^3$ s$^{-1}$) and $DA$(°). Charts to the left refer to variables monitored between slats and the charts to the right are for variables measured at 0.25 m above the slats. Dots placed above each bar represent the upper limit of the 95% confidence interval. ($p = .010$ and $p = .001$ at the slats level and at 0.25 m above slats, respectively). As for the dependent variable $TI$, in general, the barcharts in Figure 4(c) and 4(d) seem to be inversely related to those presented in Figure 4(a) and 4(b), respectively, except for lower range of $VR = 0.150$ m$^3$ s$^{-1}$, where $TI$ was likely overestimated by the very small measured $u$ values. This means that higher $TI$ values were observed where $u$ was low, and vice-versa. A similar outcome was observed by Saha et al. [38]. In addition, Townsend [41] demonstrated that the occurrence of
higher $TI$ at lower $u$ is an indication of a highly intermittent flow regime, which might be associated with a higher volatilization rate of NH$_3$.

In Figure 4(c) it can be seen that high $TI$ values were observed at low $DA$ ($0^\circ$), while in Figure 4(d) low $TI$ occurred at $DA = 90^\circ$. These relatively high values for $TI$ might not have any physical meaning concerning the description of flow characteristics, as they originated from the use of respective low $u$ values (Figure 4(a) and 4(b), respectively) plugged into Equation (1).

The results in Table 3 reveal that the variable [NH$_3$] was significantly impacted by $DA$ ($p < .001$) at the slats level. This outcome implies that when $DA$ was increased, $u$ reached higher values. In Figure 4(e) one can see that the concentrations measured between the slats were higher at lower $DA$ values, while an inverse trend was observed at 0.25 m above slats (Figure 4(c)). This outcome suggests the presence of a negative concentration gradient between the slat level and the height of 0.25 m (Figure 4(f)). A similar outcome was obtained by Mendes et al. [42] when monitoring concentrations of NH$_3$, carbon dioxide (CO$_2$) and sulfur hexafluoride (SF$_6$, artificially injected) at different heights above the slats (1–4 m) in a naturally ventilated dairy cow barn. Gaseous concentrations will tend to decrease at larger distances from the emitting source due to dilution.[20] the aqueous solution surface in the case of this study, when cross air flow is present.

In the conditions of this experiment, the statistical analysis revealed that at the slats level, $VR$ did not affect [NH$_3$] ($p = .134$). However, it was significantly affected by $DA$ ($p < .001$), both between and 0.25 m above slats.

This outcome indicates that, in the conditions of this study, $VR$ itself was not relevant to the [NH$_3$] profile, while the different air flow patterns created with different $DA$ did affect [NH$_3$] distribution between above the slats. One practical implication of this is that any $VR$ values will only enhance the volatilization and transport of NH$_3$ if air currents entering the livestock barn are diverted towards the emission surface.[14,15] On the other hand, if the main air stream remains well above the emission surface, the mass transfer will take much longer to occur.

Ye et al. [27] and Ye et al. [43], with laboratory reduced scale studies of a pig barn model with an aqueous solution of NH$_3$, indicated that inlet $VR$ did reduce [NH$_3$]. In these studies, the inlet air entered the model through ventilation flaps placed at side walls and just underneath the ceiling. This means that at least part of the fresh air entering the model passed through the slats, thus getting into direct contact with the aqueous solution. With this configuration, an interaction between $VR$ and the flow pattern itself might have significantly impacted [NH$_3$].

**Effects of HH and DA**

The regression equations resulting from the analysis on the effects of $HH$ and $DA$ on $u$, $TI$ and [NH$_3$] are given in Table 4 and the averaged values are plotted in Figure 5. The analysis indicated that within the tested range of 0.10–0.63 m, the factor $HH$ did not have a significant effect on any of the explained variables ($172 < p < .890$). This result can be seen in Figure 5(a)–5(d), meaning that no adverse effect of $HH$ on the average air velocity between or above the slats was observed. As a consequence, [NH$_3$] monitored between and above the slats (Figure 5(e) and 5(f), respectively) also remained approximately constant across different $HH$ values. This result suggests that, at a given constant $DA$, the increasing proximity of the aqueous solution surface to the slats (achieved by decreasing $HH$), and thus to the main air flow stream, did not lead to higher volatilization of NH$_3$.

Because no significant interactive effect of $HH$ was present in this study ($p = .756$), the results from this experiment can be used to specifically address the effect of guiding the air through the slats on [NH$_3$]. The significant impact of $DA$ on $u$, $TI$ and [NH$_3$] can be visualized in Figure 5 and Table 4. The factor $DA$ significantly affected all three monitored explained variables ($0.001 < p < .003$). These outcomes support the results of the experiment with $VR \times DA$ previously discussed in this study that changing air flow patterns significantly impacted [NH$_3$] distribution near the slatted floor. Morsing et al. [44] found that effects on air flow patterns inside pig barn models equipped with different manure channel layouts and floor types on average barn [NH$_3$] were significant. Those authors hypothesized that the effects on gas emissions are a consequence of changing air flow patterns and different types of flow in the boundary layer between manure and air.

| Variable | Height | Regression model |
|----------|--------|------------------|
| $U$      | At slats | $u = (0.0044 \pm 0.0005) \cdot DA$ |
| $U$      | 0.25 m above slats | $u = (-0.008 \pm 0.001) \cdot DA$ |
| $TI$     | At slats | $TI = (0.0002 \pm 0.001) \cdot DA$ |
| $TI$     | 0.25 m above slats | $TI = (0.0059 \pm 0.0009) \cdot DA$ |
| [NH$_3$] | At slats | $[NH_3] = (47 \pm 5) + (-0.37 \pm 0.09) \cdot DA$ |
| [NH$_3$] | 0.25 m above slats | $[NH_3] = (6 \pm 2) + (0.14 \pm 0.04) \cdot DA$ |
Calculations of PTC

The results for the non-linear regression performed for PTC data are presented in Figure 6(a). Figure 6(b) shows the obtained regressed curve amongst the selected models for $k_{NH_3}$ from other studies (Table 1).

It can be seen from the plot in Figure 6(b) that, for $u$ ranging between 0.1 and 0.7 m s$^{-1}$, the model for PTC from this study is quite comparable to those obtained for $k_{NH_3}$ from other studies. The average values for $k_{NH_3}$ calculated over the considered velocity range are presented.
Figure 6. Regression curve for $PTC$ of NH$_3$ (m s$^{-1}$) (a); $PTC$ curve from this study plotted together with NH$_3$ mass transfer coefficients ($k_{NH3}$, m s$^{-1}$) from other studies (b). Bar charts of the effects of $VR$ (m) versus $DA$ ($^\circ$) on $PTC$, and (c) and of the effects of $HH$ (m) versus $DA$ (d) on $PTC$, m s$^{-1}$, monitored in the test section of the wind tunnel. Dots placed above each bar represent the upper limit of the 95% confidence interval.

Table 5. Averaged mass transfer coefficients ($k_{NH3}$, m s$^{-1}$) and $PTC$ (m s$^{-1}$) of NH$_3$ calculated over the air velocity range of 0.1–0.7 m s$^{-1}$.

| Source            | Average $k_{NH3}$ or $PTC$ (m s$^{-1}$) |
|-------------------|----------------------------------------|
| Ikeguchi and Kamo [36] | 0.0015                                  |
| Ye et al. [27]    | 0.0043                                  |
| Rong et al. [37]  | 0.0027                                  |
| Saha et al. [38]  | 0.0018                                  |
| Vaddella et al. [39] | 0.0036                                 |
| This study        | 0.0039                                  |

The average $PTC$ was 0.0039 m s$^{-1}$, which was included in the range defined by the average $k_{NH3}$ of 0.0015–0.0043 m s$^{-1}$ from different studies. This outcome indicates that compared to the determination of $k_{NH3}$, the simplification added to the determination of $PTC$ by measuring gaseous concentrations between slats instead of right on top of the manure surface can still yield values that are comparable to those measured in the laboratory. The main consequence of this outcome is that the methodology for the determination of $PTC$ determined in this study could be applied to real cattle barns in order to help answering questions concerning influencing factors of the emissions from the manure pit. Although it was not the main objective of the current study, measurements of $PTC$ between slats in real dairy cattle barns are recommended in future studies.

The regression models for the variable $PTC$, similarly to the statistical models in Equations (9) and (10), are presented as Equations (12) and (13), respectively. The values of $PTC$ plotted against $VR \times DA$ and $HH \times DA$ are shown in Figure 6(c) and 6(d), respectively. For the experiment involving $VR \times DA$, a similar outcome as to what was observed for [NH$_3$] was also observed on $PTC$. In other words, $VR$ had a significant impact on $PTC$ ($p = .038$). Ye et al. [27] found that the effect of $HH$ had a relatively small, but significant inverse correlation with NH$_3$ emissions in a reduced scale model of a pig barn with aqueous solution.
On the other hand, Ni et al. [16] when monitoring NH$_3$ emissions from a full-scale pig barn, found no clear relationship between NH$_3$ emission and HH. Similar results were found by Ye et al. [45], when monitoring NH$_3$ emissions in a full-scale experimental pig room. The studies of Ni et al. [16] and Ye et al. [45] at full scale were more comparable to this study than the work described by Ye et al. [43] for reduced scale models. Whereas, a rather weak but significant effect of HH was found with reduced scale, such effect is not found in this study. This outcome might have stemmed from the fact that, although this was a wind tunnel study, care was taken that some aspects were kept close to practical situations (the slatted floor is scaled 1:1; the inlet velocity is representative of velocities that actually happen near the floor of dairy cattle barns [15] and HH values were also chosen to be realistic), which yielded PTC values that are closer to mass transfer coefficient values from studies conducted in full-scale livestock barns, than reduced scale wind tunnel ones.

On the other hand, the novelty aspect that this study brings, as compared to the results of Ni et al. [16] and Ye et al. [45], is that a full-scale section of slatted floor placed inside a wind tunnel allows for better control of the variables of interest. While in the studies of Ni et al. [16] and Ye et al. [45] the weak correlation found between NH$_3$ emissions and HH might have been due to high uncertainty levels, the increased accuracy of this study makes the non-existent effect of HH on emissions more clear:

\[
PTC = (7 \pm 3) \times 10^{-10} \cdot VR + (8 \pm 2) \times 10^{-12} \cdot DA, \\
(12)
\]

\[
PTC = (1.0 \pm 0.1) \times 10^{-11} \cdot DA, \\
(13)
\]

A positive significant effect of DA on PTC was observed in the experiment involving HH vs. DA ($p < .0001$), and can be seen in Figure 6(d). When looking at the effect of HH on PTC, the statistical analysis shows that a change in HH did not lead to a significant change in PTC. This outcome is linked to the non-significant effect of HH on $u$, TI and [NH$_3$], as previously discussed in this study. While a positive interaction existed between DA and PTC (Equations (12) and (13)), DA was negatively correlated with [NH$_3$] near the slats (Table 2). This outcome stems from the fact that the higher air velocities near the slats were associated with reduced [NH$_3$], which means that more NH$_3$ was transported from the pit to above the slats and out of the wind tunnel (higher PTC). Consequently, lower PTC values may be achieved when the main air stream is guided well above the slats.

Practical implications from this outcome might be drawn in order to reduce NH$_3$ volatilization. For instance, relatively high VR values could be practiced in a dairy cow barn in order to keep indoor air quality at its healthy levels, as long as the main airstream is placed above the animal occupied zone, such as the case of crossed flow ventilation.

The outcomes of this study indicate that the methodology for the determination of PTC in real dairy cattle barns with slatted floor is feasible and yielded results that are comparable to other laboratory studies. However, measurements of PTC in a real barn will make it cumbersome to separate the fraction of NH$_3$ transferred from the manure pit and the floor itself. Hence, adaptations to this methodology for the determination of PTC in real livestock barns must be taken. These adaptations were out of the scope of this study, and might be a subject for future research.

Conclusions

A wind tunnel system was built in the laboratory, which featured a section of a slatted floor typically used in dairy cow barns. The manure pit was represented by an NH$_3$-emitting aqueous solution. Measurements of $u$, TI and [NH$_3$] were monitored between slats and at 0.25 m above slats. PTC was calculated for the entire test section of the wind tunnel and compared with $k_{NH3}$ determined from other scientific studies. The effects of changing inlet VR, guiding the inlet air towards the slats and different HH on $u$, TI, [NH$_3$] and PTC were tested. The following conclusions can be drawn:

1. The variability of the inlet velocity and aqueous solution pH were relatively small (0.47 ± 0.01 m s$^{-1}$ and 8.02 ± 0.03, respectively), indicating that the ventilation system of the wind tunnel and the conditions of the aqueous solution presented good stability and repeatability.

2. The PTC values obtained in this study presented a good fit to the power function of the air speed near the slats ($u$) ($p < .001$) and the average PTC (0.0039 m s$^{-1}$) was comparable to $k_{NH3}$ values obtained from other studies, by remaining within the range of average values of 0.0015–0.0043 m s$^{-1}$.

3. $VR$ alone did not affect [NH$_3$] ($p = .134$). However, the change in the flow patterns near the slats (by changing DA) did impact the concentration profile and the transfer of NH$_3$ from the pit ($p = .038$).

4. Under the conditions of this study, changing the slurry pit HH from 0.10 to 0.90 m did not significantly impact [NH$_3$] ($p = .756$) or PTC ($p = .854$).

Disclosure statement

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