Study on the Influence of Velocity, Turbulence Intensity and Temperature on Ammonia Emission Rate in a Wind Tunnel

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Study on the influence of velocity, turbulence intensity and temperature on ammonia emission rate in a wind tunnel

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ABSTRACT

Odor emissions from manure in livestock buildings are an important issue which concerns the human health and air quality as well as animals. Ammonia is one of the most important odors in pig houses. The objective of this paper is to investigate the influence of local velocity, turbulence intensity and temperature on the ammonia emission rate. The experiments are conducted in a wind tunnel which is used to simulate the boundary layer of the flow above the slurry. The results show that the emission rate of ammonia increases with increasing velocity and turbulence intensity as expected. The results also show that decreasing the temperature of ammonia aqueous solution decreases the ammonia emission rate dramatically, but the emission rate is more sensitive to the change of temperature at higher compared to lower temperature range. The mass transfer coefficient is inversely proportional with the Reynolds number and also inversely proportional with the Archimedes number.
Key word: ammonia emission rate, velocity, turbulence intensity, temperature

INTRODUCTION

Indoor air quality is an important issue related to the health of workers and animals in livestock buildings. In a survey of about 8000 randomly selected farmers in some European countries, it's stated that farmers working at pig houses are at the highest risk (27.3%) among agricultural workers for the development of work-related respiratory symptoms [1]. It is reported that there are about 130 pollution gases found in livestock buildings [2]. Ammonia is one of the most important pollutant gases produced in pig houses.

A review of the existing mass transfer coefficient models for ammonia showed that ammonia emission is commonly correlated to air velocity and liquid properties [3]. The influence of air velocity and temperature on NH_3 emission from liquid surface has been studied by several researchers. The mass transfer coefficient of ammonia in liquid swine and aqueous solutions was observed to increase with increasing air velocity and liquid temperature but decreased with increasing air temperature [4]. For the ammonia release from aqueous solutions, it is also found that the higher ventilation rate will increase ammonia emission as expected in a small wind tunnel with cross-section in 150mm×150mm [5]. But he also observed that the peak value of the mass transfer coefficient occurred at various ventilation rate when the PH value of the liquid varied. The ventilation control strategies will change the velocity distribution in the building and the impact on ammonia emission is also studied. Among three control strategies which are constant inlet opening area, constant inlet air velocity and constant inlet air jet momentum, the highest emission rate was found for constant inlet opening in a 1:12.5 scaled model. The impact of other factors such as turbulence intensity, manure properties and animal's numbers or weight has also been investigated experimentally.

The above review indicates that there is a general agreement that ammonia emission from aqueous solution can be affected by local velocity, turbulence intensity and temperature, but the specific details in boundary layer of each individual factor are needed to be further investigated. It can probably provide some important information of mass transfer in boundary layer and help to understand the mass transfer process better.

Comparing with the full scale experiment, wind tunnel experiment is cheaper and easier to control environmental parameters such as local velocity and turbulence intensity. Using wind tunnel techniques, terrain and topographical features can be controlled and useful data translatable to real life situations can be obtained for a wide range of air pollution problems [7]. There are many literatures studying on odor emission in wind tunnel. The gas sampling efficiency and aerodynamic characteristics of a laboratory wind tunnel for odor measurement is studied. It shows that the average gas recovery efficiency is around 81% [8]. Odor emission rates from cattle feedlots were sampled at two different size wind tunnels and the emission rates are shown to be strongly correlated [9]. In order to evaluate the wind tunnel technique for estimating ammonia volatilization from land, the experiments of determining the transfer characteristics is reported in reference [10] and [11]. In this paper, wind tunnel is also adopted to conduct the experiments.

The main objectives of this paper are: (1) to investigate the impact of air velocity, temperature difference between the air and ammonia solutions and turbulence intensity on ammonia emission rate; (2) to obtain the relation between the mass transfer coefficient and the Reynolds number and Archimedes number.

THEORETICAL BACKGROUND

The room airflows are usually turbulent. The boundary layer along a wall has a laminar sub-layer, but it becomes turbulent in some distance. The boundary layer therefore consists of a thin laminar sub-layer, a buffer layer and a turbulent layer. There exists a set of universal profiles, the so-called wall-laws or wall functions for velocity, in the turbulent boundary layer.

$$u_* = \sqrt{\frac{\tau_w}{\rho}}, \quad (1)$$

$$y^+ = \frac{\rho y u_*}{\mu}, \quad (2)$$

$$u^+ = \frac{u}{u_*} = \frac{1}{k}\ln y^+ + B, \quad (3)$$

Where τ_w is the wall shear stress, N/m^2; ρ is air density, kg/m^3; μ is dynamic viscosity, kg/ms; u_* is the friction velocity m/s; y^+ is dimensionless distance; u^+ is dimensionless velocity; u is the velocity in main flow direction, m/s; and y is distance from the wall, m. White [12]suggests $B \approx 5.0$ for turbulent flow past smooth impermeable walls and the Karman constant $k \approx 0.41$.

The typical velocity profile for turbulent boundary layer flow is shown in Figure 1. As a rough approximation, this transition region from laminar sub-layer to fully turbulent layer has been ignored. Thus there is a sudden transition from the turbulent core to the laminar sub-layer in which:

$$u^{+} = y^{+}, \quad (4)$$

$$c^{+} = \frac{u_{*}(c_w - c)}{E_w} = Sc * y^{+}, \quad (5)$$

Where c^{+} is the dimensionless concentration; E_w is the emission rate, kg/s; c_w is the surface concentration, kg/m^3; c is the concentration in the bulk air, kg/m^3 and Sc is the Schmidt number. The two velocity profiles intersect at $y^{+} \approx 11.6$, the profiles for concentration are similar in shape. Generally, there are two definitions for boundary layer thickness of velocity which are δ_{99} and displacement thickness. In Figure 1, the boundary layer thickness for velocity profile, δ, is defined as the distance from the wall where the velocity is equal to the bulk air velocity along the velocity linear function in laminar sub-layer. This definition is equivalent to the concentration boundary layer thickness definition δ_D used in the future work. δ_D represents the same resistance to diffusion as encountered in the combined process of molecular and turbulent diffusion [13].

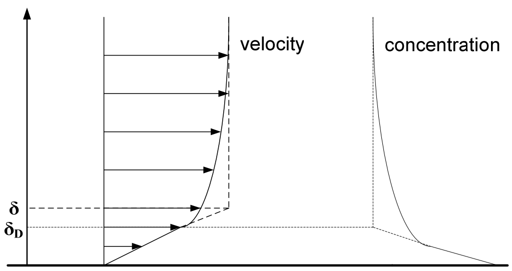


Figure 1 Typical velocity profile for boundary layer flow

The emission from surface can be determined by convective mass transfer coefficient and the difference between the concentration at the surface and concentration in the bulk air:

$$E_w = h_c A(c_w - c), \quad (6)$$

Where h_c is the convective mass transfer coefficient, m/s and A is the emission area, m^2. Considering the emission rate from the surface with the concentration difference between the outlet and inlet of the wind tunnel under steady state conditions, the emission rate can also be expressed as:

$$E_w = Q(c_r - c_i), \quad (7)$$

Where Q is the ventilation rate, m^3/s; c_r is the concentration at the outlet, kg/m^3; and c_i is the concentration at the inlet, kg/m^3. Therefore, if the concentration at the surface can be determined, the mass transfer coefficient h_c can be calculated. Based on the boundary layer theory, $c_w - c$ is calculated by equation (5) with the assumption that the laminar sub-layer meet with turbulence core at the same Yplus value with both velocity and concentration.

MATERIAL AND METHOD

3.1 ammonia aqueous solution

In order to keep the ammonia concentration constant, the ammonia aqueous solution is made from NH_4CL, Na_2CO_3 and $NaHCO_3$. NH_4CL is the original source for ammonia release and Na_2CO_3 and $NaHCO_3$ consist of the buffer solution to keep the solution PH varying little. It's known that PH value has an important effect on ammonia gas concentration. There are two tanks stored 180L ammonia aqueous solution. One tank is used to supply the ammonia aqueous solution to the wind tunnel container and the other one is used to store the return ammonia aqueous solution, see Figure 2. The 'Total Ammonia Nitrogen' (TAN) was measured before and after experiments every day as well as PH value and temperature of ammonia aqueous solution. The TAN is 6800mg/l and PH value is 8.98 with temperature in 22.3℃. It should be mentioned that the PH and TAN in experiment is higher than the value in pig manure to obtain higher ammonia concentration in the air which makes the measurement easier.

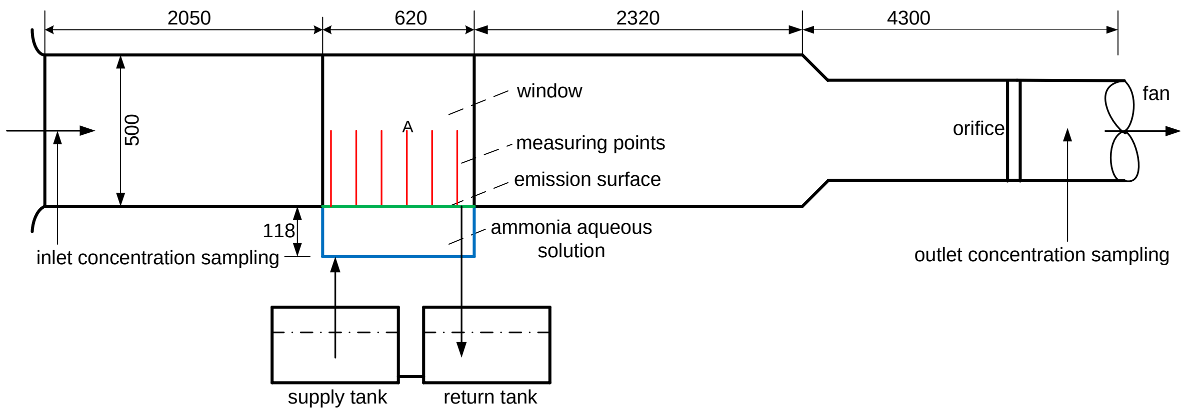


Figure 2 Sketch of wind tunnel system connected with two tanks in experiment

3.2 Experiment design and set-up

All experiments are conducted in the wind tunnel which is designed to study the gas emission or particle flows, and thus, is ideal for simulating the emission of ammonia. The wind tunnel is well designed with rounded inlet surface to supply a uniform air flow. The test facilities consist of the rectangular wind tunnel with emission area, a cone shaped connection and circle outlet stainless tube. The emission surface area is 0.62m*0.43m and the other sizes of the wind tunnel are shown in Figure 2. The investigations are performed with four temperatures of ammonia aqueous solution, four mean velocities and three turbulence intensities, see table 1.

Table 1 experiment set-up

TAN (mg/l)	PH	velocity (m/s)	Turbulence intensity (%)	Ammonia aqueous solution temperature (℃)	Air temperature (℃)
6800	8.98	0.1	10, 16, 35	6.5, 10.5, 15, 22	22
		0.2	10, 16, 35	6.5, 10.5, 15, 22	22
		0.3	10, 16, 35	6.5, 10.5, 15, 22	22
		0.4	10, 16, 35	6.5, 10.5, 15, 22	22

Before starting experiment every day, the wind tunnel was running for 1 hour to reach steady condition and all doors were locked during the experiments. Velocity and velocity fluctuation were measured by a Laser Doppler Anemometer. The measuring time of every point at various velocity and turbulence intensity was studied to obtain the real average velocity so that the measuring time varied from 6min to 25min. Temperature in the boundary layer is measured by thermocouples and temperature and humidity at outlet and inlet is also measured. Airflow rate was measured by orifice. The data of pressure drop through the orifice was recorded by a data collector and monitored on the computer all the time.

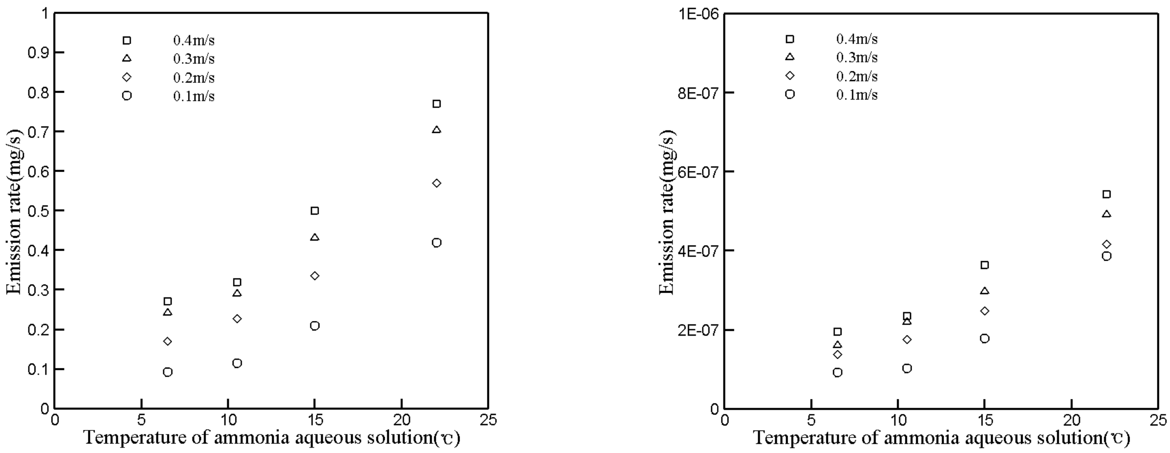
Ammonia concentration was measured by Photoacoustic Multi-gas Monitor and Multiplexer, which was calibrated just before measurement. The sample integration time was 20s and the measuring time for every point was 45min. It should be mentioned that the concentration of inlet, outlet and boundary profiles was not measured simultaneously. For example, the inlet concentration was measured for 45min and then the outlet concentration was measured for another 45min. TAN is measured based on ISO 7150/1 and PH is measured by a PH detector.

RESULTS AND DISCUSSION

4.1 Impact of air velocity, turbulence intensity and liquid temperature on ammonia emissions

To examine the effects of velocity, turbulence intensity and ammonia aqueous solution temperature on ammonia emissions, a series of experiments have been conducted in wind tunnel in which all the parameters are kept the same as those of the reference case except for the one to be examined. The inlet air temperature of the wind tunnel is kept the same as 22±1℃in all tests and the turbulence intensity value is taken from point A above the emission surface, see Figure 1.

Figure 3 shows the ammonia emission rate under different air velocities ranging from 0.1m/s to 0.4m/s, temperature of ammonia aqueous solution from 6.5℃ to 22℃ and turbulence intensity in 10% and 35%. The results present that the emission rate are significantly higher at a higher temperature that the temperature difference between the ammonia aqueous solution and the air flow is smaller. As the emissions are likely dominated by evaporation in the experiments, the emission rates depend on the equilibrium vapor pressure of emitted ammonia, which is higher for a higher temperature. Meanwhile, the emission rate is more sensitive to temperature change at higher compared to lower temperature range.



(a) Turbulence intensity in 35% (b) Turbulence intensity in 10%

Figure 3 Influence of velocity and temperature of ammonia aqueous solution on emission rate

Figure 4 shows the ammonia emission rate under different air velocity ranging from 0.1m/s to 0.4m/s. The results show that the emission rate increases with higher velocity. Based on the mass transfer theory, greater air velocity will generate bigger mass transfer coefficients. Furthermore, according to boundary layer theory, increasing air velocity results in a thinner boundary layer on the liquid surface which leads to a higher emission. Meanwhile, the emission rate is more sensitive to changes in air velocity at lower compared to higher velocity ranges, which is also reported in Arogo et al (1999). The results also show that the emission rates are increasing with higher turbulence intensity, but the turbulence intensity has little impact on the emission rate when the velocity is 0.1m/s.

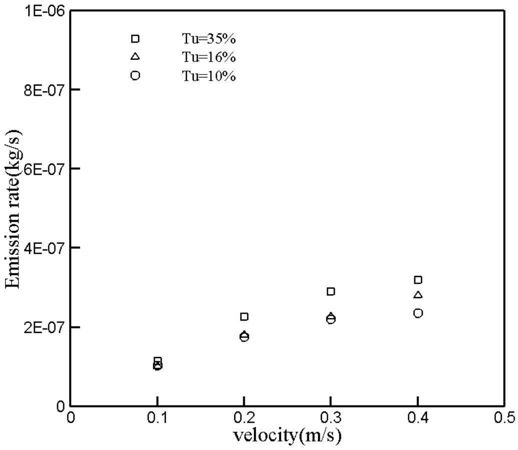


Figure 4 ammonia emission rates along velocity with liquid temperature in 10.5℃

4.3 The relation between mass transfer coefficient and Re,Ar

Traditionally, a convective emission chamber or wind tunnel etc is used to measure the emission characteristics of ammonia. One goal of emission testing is transforming the measured emission data in emission chamber or wind tunnel to actual livestock buildings for the purpose of odor emission control and health evaluation. There could be two kinds of Reynolds numbers and Archimedes number defined by either the wind tunnel height or velocity boundary layer thickness.

$$\mathrm{Re}_H = \frac{\rho U H}{\mu}, \quad (8)$$

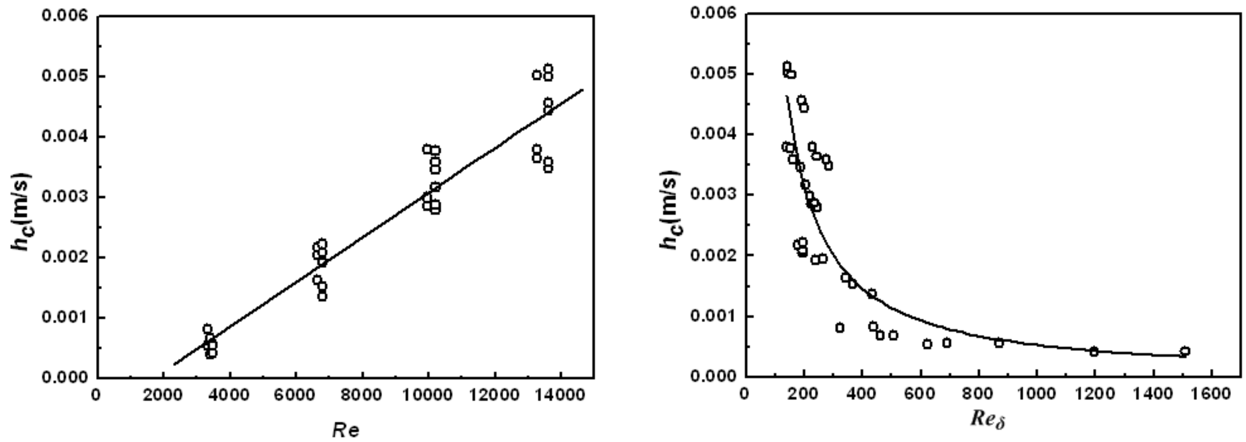
$$\mathrm{Re}_\delta = \frac{\rho U \delta}{\mu}, \quad (9)$$

$$Ar_H = \frac{g(T_a - T_l)H}{T_a U^2}, \quad (10)$$

$$Ar_\delta = \frac{g(T_a - T_l)\delta}{T_a U^2}, \quad (11)$$

Where Re_H and Ar_H is Reynolds number and Archimedes number respectively based on the height, H (m), of the wind tunnel; Re_δ and Ar_δ is the local Reynolds number and the local Archimedes number respectively based on the boundary layer thickness for velocity; U is the mean velocity, m/s; g is the gravity, m/s^2; T_a is the inlet air temperature, ℃ and T_l is the liquid temperature, ℃.

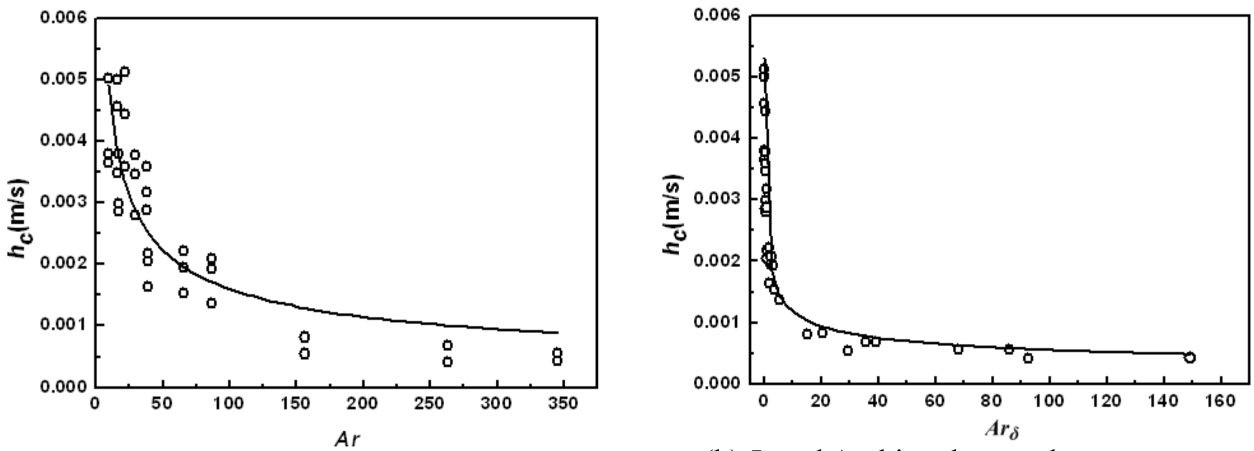
Figure 5 shows the relation between mass transfer coefficient and Reynolds number. It is seen that the mass transfer coefficient is positive linear with the Re but inversely proportional with Re_δ. With lower velocity, the boundary layer thickness is bigger and it increases faster than the velocity so that the local Reynolds number is higher. It is seen that the mass transfer coefficient varies differently with the two Reynolds number. Therefore, it is important to choose the right one when transferring the experiment data to application in actual livestock buildings.



(a) Reynolds number
(b) Local Reynolds number

Figure 5 Relation between mass transfer coefficient and Re_H **,** Re_δ

Figure 6 show the relation between mass transfer coefficient and Archimedes number. The mass transfer coefficient is inversely proportional with both Ar and Ar_δ. It can be obtained easily by mathematical analysis that the local Archimedes number can present better sensitivity of mass transfer to liquid temperature change at higher compared with lower temperature range.



(a) Archimedes number
(b) Local Archimedes number

Figure 6 Relation between mass transfer coefficient and Ar , Ar_δ

CONCLUSION

A series of experiment has been conducted to investigate the effects of air velocity, turbulence intensity and temperature on ammonia emission rate. The following conclusions can be made based on the experiment data:

(1) The ammonia emission rate increases with higher velocity and turbulence intensity, but the emission rate is more sensitive to the change of velocity at lower compared to higher

velocity range. The turbulence intensity has little impact on the emission rate when the velocity is low.

(2) The ammonia emission rate increases with higher liquid temperature, but the emission rate is more sensitive to the change of temperature at higher compared to lower temperature range.

(3) The ammonia mass transfer coefficient is positive linear with Reynolds number but is power decayed with local Reynolds number.

(4) The ammonia mass transfer coefficient is inversely proportional with both Archimedes number and local Archimedes number.

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