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Research Paper

Similarity criteria for estimating gas emission from scale models

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Similarity, or the relationship between a model and a prototype, is an important issue when using physical modelling techniques. The objective was to investigate similarity criteria using Reynolds number (*Re*) and jet momentum ratio (*Rm*) in two scale models (SM-1 of 1:6 and SM-2 of 1:12.5) of a pig house under isothermal conditions to predict airflow and ammonia emission. Experiments were conducted using two ventilation control strategies (constant inlet opening and constant inlet velocity) in SM-1 and SM-2 by (1) keeping the same inlet *Re* with constant inlet opening, and (2) keeping the same *Rm* with constant inlet opening and constant inlet velocity. Aqueous ammonia solutions, with four different total ammoniacal nitrogen (TAN) concentrations and two different pH levels, were used as emission sources inside the scale models. Non-dimensional normalised emission rate, defined as the ratio of the measured emission rate and the reference emission rate at inlet air velocity of 1 m s^{-1} of the scale models, was proposed for when using *Re* and *Rm* as similarity. *Rm* was found to be a better scaling parameter than *Re* for predicting the influence of airflow on ammonia emission rate when using the non-dimensional normalised emission rate in scale models with both ventilation control strategies and ammonia solutions of different TAN and pH.

1. Introduction

Gas and odour emissions from livestock production buildings are major air pollutants to the environment. They are mostly transported by air motion from slurry surface to the room space and eventually to the outside environment. Ventilation is important to regulate indoor environment and keep an appropriate microclimate for the thermal comfort and air quality of the occupants and farm workers. Ventilated airflow inside an enclosure influences the air distribution, thermal environment, and contaminant concentration (Aarnink & Wagemans, 1997; Saha, Zhang, Kai, & Bjerg, 2010; Topp, Nielsen, & Heiselberg, 2001; Zhang et al., 2008; Zhang et al., 2005). Jet air supplies are used in most mechanically ventilated rooms. The performance of air-jets determines the distribution of thermal energy, moisture, and fresh air inside the rooms (Awabi, 1991) as well as gas and odour emissions from the rooms (Morsing, Strom, Zhang, & Kai, 2008).

The characteristics of enclosed air-jets and their effect on gas emissions have been studied by using prototype buildings, scale models, and numerical simulation (Buller & Hellickson, 1978; Morsing et al., 2008; Strom, Zhang, & Morsing, 2002;

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Nomenclature

A	area, m^2
C	ammonia concentration, mg m^{-3}
D	diameter of exhaust pipe, m
ds	depth of ammonia pan, m
E	emission rate, mg s^{-1} m^{-2}
Eu	Euler number
Fr	Froude number
g	gravitational acceleration rate, m s^{-2}
H	model or prototype height, m
h	air inlet opening height, m
L	model or prototype length, m
Lf	flap length, m
n	geometry scale ratio of prototype to model
Re	Reynolds number
Rm	jet momentum ratio, m^2 s^{-2}
Sw	width of ammonia pan emission surface, m
SM	scale model
W	model width, m
U	mean air velocity, m s^{-1}
μ	dynamic viscosity, N s m^{-2}
ρ	density of air, kg m^{-3}
ΔP	pressure difference, N m^{-2}

Subscripts

i	inlet
m	model
max	maximum
o	outlet
p	prototype
r	return air
s	ammonia release surface
t	sum of inlet cross-sections of two side walls
1	test condition at inlet velocity of 1 m s^{-1}

Zhang et al., 2008). However, precise mathematical models are not feasible for the extremely complex micro-structures occurring in room airflows (Yu, Jou, Ouyang, Liang, & Liao, 2006).

Experiments with full scale buildings are expensive and it is often difficult to observe the specific behaviour of airflow and emission by controlling parameters such as wind velocity, humidity, air temperature etc. Therefore, scale model tests are necessary if dimensional uncertainty is not known and a precise mathematical-physical prediction model is not established. Scale model studies are practical for simulating the air motion of a prototype and can be used to validate numerical simulations. Similarity, or the relationship between a model and a prototype, is an important issue for experiments with scale models. Similarity analysis can be a useful technique for predicting the performance of a prototype animal housing system from scaled models (Adre & Albright, 1994). Nevertheless, only partial similarity between the model and the prototype is satisfied for most of the dimensionless parameters because usually there is conflict between the similarity requirements.

Reynolds number (*Re*) has been widely used as the similarity parameter for an isothermal airflows in scale models (Jin & Ogilvie, 1992; Pattie & Milne, 1966; Timmons & Baughman, 1981). However, differences in inlet air velocity profiles between the model and the prototype can result in greater dimensionless inlet jet momentum for the scale model even though the inlet *Re* remains the same, especially when the room airflow is not fully turbulent (Adre & Albright, 1994; Yu et al., 2006; Yu & Hoff, 1999; Zhang, Christianson, & Riskowski, 1991). The jet momentum ratio (*Rm*), or the ratio of the inlet jet momentum and the momentum loss due to shear along the enclosure walls, has been validated as an appropriate scaling parameter for airflow pattern similarity under isothermal conditions. However, direct comparison studies of the effect of *Re* and *Rm* on gas emission, have not been found in the literature.

When comparing the similarity between gas emission rates from two models, there can be differences in prevailing conditions, i.e., the temperature, moisture content, concentration of aqueous solution/source, pH value, and emission surface area etc. To reduce these effects, Smith and Watts (1994) used a non-dimensional emission rate (E_1) for comparing two wind tunnel results, where E_1 was the emission rate at a velocity of 1 m s^{-1}. This was viewed as a base emission rate for the prevailing conditions. However, limited knowledge is available on the similarity of gas emission estimates using scale model experiment data.

Laboratory experiments were conducted on ammonia emissions from two 1:6 and 1:12.5 scale models of a pig barn operating under isothermal conditions. The objectives of this work were to 1) investigate *Re* and *Rm* as similarity parameters for estimating airflow and gas emissions from scale models, and 2) assess two-dimensional wall jet air flow patterns in confined spaces and their effect on gas emissions using scale models.

2. Theory

Complete similarity of turbulent plane-wall air-jets diffused into a slot-ventilated enclosure under isothermal conditions requires geometric, kinematic, and dynamic similarity, and similar boundary conditions (Awabi, 1991; Baturin, 1972; Szucs, 1980; Yu & Hoff, 1999). Similarity of boundary conditions must occur to reach complete similarity between geometric, kinematic and dynamic conditions at all solid boundaries of the model and prototype. Geometric similarity requires the model to be the same shape as the prototype, usually scaled. In kinematic similarity, fluid flow of both the model and prototype must undergo motion changes with similar time scales, i.e., accurate scaling flow boundaries including air supply opening, exhaust outlet, and roughness of all surfaces. Dynamic similarity requires the ratios of all forces acting on corresponding fluid particles and boundary surfaces, including inertial, viscous, pressure, and buoyant forces to be kept constant.

Similarity analysis indicates that similarity parameters for isothermal airflow are geometry, Froude number (*Fr*), Reynolds number (Re), and Euler number (Eu) between the model and the prototype. The Fr represents the ratio of inertial to gravitational forces:

$$Fr = \frac{U_i}{\sqrt{gL}} \quad (1)$$

where Fr is Froude number; U_i is mean inlet air velocity at air inlet, m s^{-1}; g is gravitational acceleration rate, m s^{-2}; L is model or prototype length, m.

For isothermal airflow in a slot-ventilated enclosure, Fr does not need to be considered, because it is only important for compressible flows and for motions with free liquid-vapour surfaces (Schilchting, 1979). The Reynolds number Re has traditionally been used as the scaling factor; but an anomaly in the use of Re as the kinematic similarity parameter for the scale modelling of slot-ventilated enclosures has occurred (Rousseau & Albright, 1996). For isothermal conditions Re represents the ratio of inertial to viscous forces:

$$Re = \frac{\rho U_i h_i}{\mu} \quad (2)$$

where Re is Reynolds number; ρ is density of air, kg m^{-3}; h_i is inlet opening height, m; μ is dynamic viscosity, N s m^{-2}.

Similarity between the model and the prototype requires:

$$\left(\frac{\rho U_i h_i}{\mu}\right)_m = \left(\frac{\rho U_i h_i}{\mu}\right)_p \quad (3)$$

where subscripts m and p represent scale model and prototype, respectively.

If the same working fluid is used in the model and the prototype, then $\rho_{m\,=}\,\rho_p$ and

$\mu_m = \mu_p$, resulting in the following requirement between diffuser airspeeds:

$$\frac{U_{i,m}}{U_{i,p}} = \frac{h_{i,p}}{h_{i,m}} = n \quad (4)$$

where $U_{i,m}$ is mean inlet velocity of the model, m s^{-1}; $U_{i,p}$ is mean inlet velocity of the prototype; $h_{i,p}$ is inlet opening height of the prototype, m; $h_{i,m}$ is inlet opening height of the model; n is the geometric scale between the model and the prototype.

For slot-ventilated enclosures, Re has a negligible effect on the governing equations of fluid dynamics compared with that of the Euler number (Eu), which becomes an alternative kinematic similarity parameter instead of Re (Rousseau & Albright, 1996). The Eu represents the ratio of pressure to momentum forces:

$$Eu = \frac{2\Delta P}{\rho U_i^2} \quad (5)$$

where Eu is Euler number; ΔP is total pressure difference between inlet and outlet, N m^{-2}.

For a two-dimensional wall jet in mechanically ventilated spaces under isothermal condition, Eu may not be the appropriate similarity parameter (Yu et al., 2006). In scale model studies with confined wall jets where airflow pattern and air-jet penetration distance similarity were measured, the jet momentum ratio (Rm) was proposed (Adre & Albright, 1994) and verified (Adre & Albright, 1994; Yu et al., 2006; Yu & Hoff, 1999) as a more appropriate scaling criterion. Rm is functionally equivalent to the Eu number for similarity in diffuser airspeeds between a scale model and a prototype. The Rm was defined by Adre and Albright (1994) as:

$$Rm = \frac{U_i^2 h_i}{L + H} \quad (6)$$

where Rm is jet momentum ration, m^2 s^{-2}; H is model or prototype height, m.

The Rm implies that, to acquire similar wall jet flows in slotted inlet ventilated enclosures of different sizes, the jet momentum at the inlet (source) must vary proportionally to the cross-sectional perimeter of the enclosure.

Using Rm as the similarity criterion, the design condition between the model and the prototype is

$$\left(\frac{U_i^2 h_i}{L + H}\right)_m = \left(\frac{U_i^2 h_i}{L + H}\right)_p \quad (7)$$

as

$$\left(\frac{h_i}{L + H}\right)_m = \left(\frac{h_i}{L + H}\right)_p \quad (8)$$

the relationship further simplifies to:

$$U_{i,m} = U_{i,p} \quad (9)$$

In this study, two similarity parameters Re and Rm are compared for estimating floor level airflows and gas emissions using two scale models.

3. Materials and methods

3.1. *Experimental facilities*

The experiments were carried out in Air Physics Laboratory, Faculty of Agricultural Sciences, Aarhus University, Denmark. Two geometrically similar scale models representing a pig grower barn were used to study airflow parameters and ammonia emissions. The 1:6 and the 1:12.5 scale models were denoted as SM-1 and SM-2, respectively, and are illustrated in Fig. 1. The dimensions of SM-1 and SM-2 are given in Table 1. The scale models were made of thick transparent acrylic plastic. Ventilation air was supplied through adjustable flaps at two sides beneath the ceiling. The flaps spanned the whole width of the model with maximum opening heights of 0.095 m and 0.045 m for SM-1 and SM-2, respectively. Exhaust air was extracted using variable-speed axial-flow ventilation fans type K315 L (System air AB, SE-739 30 Skinnskatteberg, Sweden) and type QBU100D (Lindab, Denmark) through 0.070 and 0.035-m internal diameter pipes for SM-1 and SM-2, respectively. A Lubcke VARIO® variable transformer drive (type RV10806-20, Noratel Lubcke A/S, Brondby, Denmark) and a Danfoss VLT® variable-speed drive (type 3508, Danfoss A/S, Nordborg, Denmark) were used to control fan speeds for SM-1 and SM-2 respectively.

A duct was fitted between the circular exhaust port and the exhaust fans. A calibrated FMU/FMDRU 100–80 flow meter (Lindab A/S, Haderslev, Denmark) and an orifice plate were used to select desired airflow rates through SM-1 and SM-2, respectively. In SM-1, the pressure difference between the upstream and the downstream side of the flow meter, was

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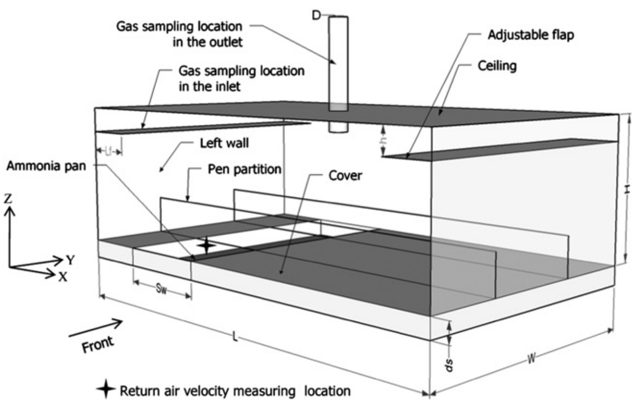

Fig. 1 – Schematic diagram of the scale models used in the study.

measured using a differential pressure sensor (Model 694, Huba Control, Würenlos, Switzerland), which had a measurement range of 10–300 Pa, an accuracy of ± 0.7%, and a resolution of 0.1% of full scale. In SM-2, pressures across the orifice plates were measured by a Micro-manometer (type FC0510, Furness Control Ltd., East Sussex, England), which had a measurement range of 0–2000 Pa, an accuracy of 0.3% and a resolution of 0.01 Pa. The averaged data of a sampling period of 1s were saved every min in a data logger (Model CR215, Campbell Scientific, Logan, Utah, USA).

At a distance of 1/4 the length from the left sidewalls, 0.980 m × 0.375 m and 0.500 m × 0.180 m surface areas of the uncovered ammonia pans were used in SM-1 and SM-2, respectively (Fig. 1). The remaining bottom surface areas were covered with 0.005 m thick polystyrene sheet in SM-1 and 0.001 m thick neoprene in SM-2.

3.2. Ammonia aqueous solution

The aqueous solutions of ammonia used for the experiment were combinations of a source solution and a buffer solution. An ammonium chloride (NH_4Cl) solution was made as the ammonia source. The buffer solution of sodium carbonate (Na_2CO_3) and sodium hydrogen carbonate ($NaHCO_3$) was used to keep the constant pH of the aqueous solution. The solution was kept circulating during the measurement at the flow rate of 0.05 m^3 hr^{-1} using a 6-mm diameter hose and a pump (type PA1000, Heissner GmbH, Lauterbach, Germany) from the ammonia source tank. This kept a 0.25 m deep ammonia solution underneath the scale model and fed the ammonia pan inside the model. The stability of the ammonia aqueous solution was tested prior to the experiment to ensure that the ammonia emission rate under specific conditions could allow the experiment to be performed under steady state conditions. The continuous circulation of solution in the ammonia pan provided a stable free ammonia concentration at the immediate liquid surface even during the ammonia release process.

Liquid samples were taken from the return flow of the ammonia solution before and after each experiment to measure the total ammoniacal nitrogen (TAN) concentration according to ISO 7150/1 and the pH value using a pH detector (type Sension 1, HACH-LANGE, Bronshoj, Denmark).

Table 1 – Dimensions of the two scale models SM-1 (1:6) and SM-2 (1:12.5).

Parameters	SM-1, m	SM-2, m
Model length, *L*	1.750	0.840
Model width, *W*	1.000	0.500
Model height from the emission surface, *H*	0.535	0.290
Maximum inlet opening height, h_{max}	0.095	0.045
Diameter of exhaust pipe, *D*	0.070	0.035
Flap length, *Lf*	0.188	0.090
Width of ammonia pan emission surface, *Sw*	0.375	0.180
Depth of ammonia pan, *ds*	0.070	0.130

3.3. Experimental design

To create different airflow conditions above the liquid surface, the experiments were carried out using four airflow rates and two ventilation control strategies (constant inlet opening and constant inlet velocity). Three set-ups were used during the four experiments. Set-up 1 and set-up 2 were conducted with constant inlet opening and constant inlet velocity, respectively. The same *Rm* was kept between the two models at corresponding ventilation rates in both set-ups (Table 2). In set-up 3, a constant inlet opening was used and *Re* was kept the same between the two models at the controlling ventilation rates (Table 3). Three different TAN concentrations were used in SM-1 to study the effect of TAN on total ammonia emission rate. Ammonia solutions with TAN 8400 mg l^{-1} (pH 9.0) and 23000 mg l^{-1} (pH 8.7) were used for set-ups 1 and 2. Ammonia solution with TAN of 6700 mg l^{-1} (pH 9.0) was used in set-ups 1 and 3. These selected TAN concentrations were higher than found in the pig manure in order to facilitate the study and maintain a robust balance between ammonium and ammonia during the experiment. Ammonia aqueous solution with TAN concentration of 5100 mg l^{-1} and pH of 8.7 was used in SM-2 in all three set-ups.

3.4. Measurement

Temperature and the relative humidity (RH) of the air in the experimental room and the SM-1 exhaust air were measured using two Vaisala Intercap humidity and temperature probes (Humitter 50Y, Vaisala, Helsinki, Finland) that had accuracies of ±0.1 °C for temperature and ±3% at 20 °C for RH. The air temperature and RH data were averaged and saved every minute in a data logger (Model CR215, Campbell Scientific, Logan, Utah, USA). During the SM-2 study, the room air temperature and RH were monitored with a Testo 174 mini temperature/humidity data logger (Testo Inc., Sparta, NJ, USA).

Smoke was used in the experiments to visualise the direction of the local air stream flow paths and the pressure differentials. Measurements of return air velocity and turbulent intensity were taken at non-dimensional measurement height (measurement point height/total height (H)) = 0.035 above the ammonia emission surface in both scale models at

Table 2 – Experimental set-ups 1 and 2 with two ventilation control strategies to keep similar *Rm* in two scale models.

Set-up	Control strategy	*Rm*, $m^2\ s^{-2}$	Inlet velocity, $m\ s^{-1}$	SM-1			SM-2		
				Inlet opening, m	Ventilation, $m^3\ s^{-1}$	*Re*	Inlet opening, m	Ventilation, $m^3\ s^{-1}$	*Re*
1	Constant inlet opening	0.0044	1	0.01	0.02	700	0.005	0.005	350
		0.0177	2	0.01	0.04	1400	0.005	0.010	700
		0.0398	3	0.01	0.06	2100	0.005	0.015	1050
		0.0708	4	0.01	0.08	2800	0.005	0.020	1400
2	Constant inlet velocity	0.0044	1	0.01	0.02	700	0.005	0.005	350
		0.0088	1	0.02	0.04	1400	0.010	0.010	700
		0.0133	1	0.03	0.06	2100	0.015	0.015	1050
		0.0177	1	0.04	0.08	2800	0.020	0.020	1400

Table 3 – Experimental set-up 3 with one ventilation control strategy to keep similar *Re* in two scale models.

Set-up	Control strategy	*Re*	SM-1				SM-2			
			Inlet opening, m	Inlet velocity, $m\ s^{-1}$	Ventilation, $m^3\ s^{-1}$	*Rm*, $m^2\ s^{-2}$	Inlet opening, m	Inlet velocity, $m\ s^{-1}$	Ventilation, $m^3\ s^{-1}$	*Rm*, $m^2\ s^{-2}$
3	Constant inlet opening	350	0.01	0.5	0.01	0.0012	0.005	1.0	0.005	0.0044
		700	0.01	1.0	0.02	0.0044	0.005	2.0	0.010	0.0177
		1050	0.01	1.5	0.03	0.0098	0.005	3.0	0.015	0.0398
		1400	0.01	2.0	0.04	0.0175	0.005	4.0	0.020	0.0708

corresponding ventilation rates and inlet air velocities (Fig. 1). The return air velocity is the velocity of the floor air at above mentioned height of rotary air jet. A laser Doppler anemometer (Type 58N40-FVA enhanced, DANTEC Dynamics, Skovlunde, Denmark) was used to measure the air velocity and velocity fluctuations associated with turbulence or unsteadiness. The integration time for velocity measurement at each measurement point was 8 min. The inlet air velocity was calculated using the mean ventilation rate divided by the model inlet cross-sectional area.

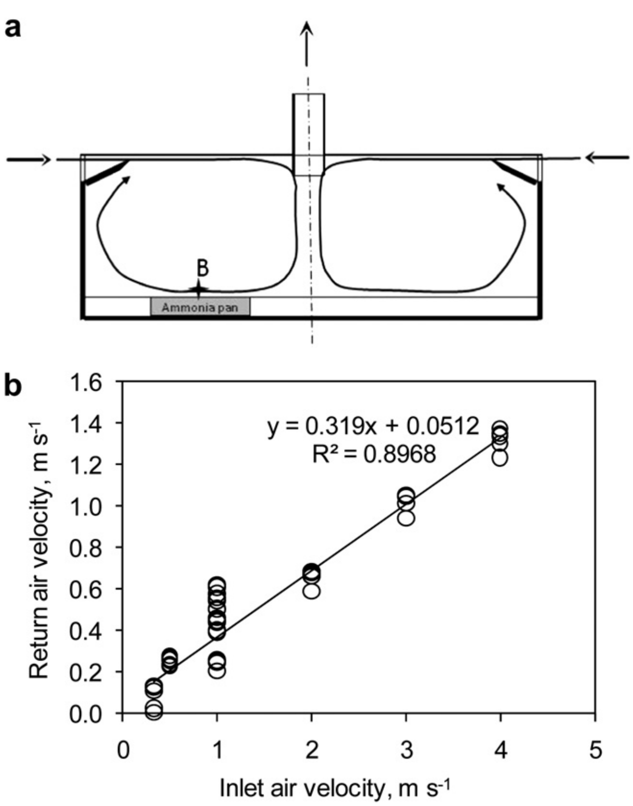

Fig. 2 – (a) Air flow pattern in a model pig house from smoke test and (b) relationship between inlet air velocity and return air velocity measured at location B.

Ammonia concentration in the incoming and outgoing air was measured sequentially at the scale model inlet and outlet, respectively, using a Brüel & Kjær Photoacoustic Multi-gas Monitor (Type 1312, Innova AirTech Instruments, Ballerup, Denmark) and a multiplexer (Type 1309, Innova AirTech Instruments, Ballerup, Denmark). The accuracy of the Multi-gas monitor for ammonia measurement was ± 0.1 ppm depending on the filter setting. The sample integration time configured in the monitor for the experiment was 20 s. The measurement period at each point was 40 min before switching to another point. It was found that at least 10–15 min were required for the ammonia concentration reading to stabilise following a measurement of air with higher ammonia concentration. Therefore, the ‘old’ air in the instruments was flushed to ensure the replacement of new air, especially when ammonia concentration of ‘old’ air was very high (Rom & Zhang, 2010). The system operated for at least 30 min to let the airflow conditions to stabilise in each experiment before ammonia concentrations were measured.

3.5. *Estimation of ammonia emission rate and calculation of non-dimensional parameters*

Ammonia emission from the scale models were calculated as:

$$E = U_i \frac{A_t}{A_s}(C_o - C_i) \tag{10}$$

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Table 4 – Experimental conditions and study results in SM-1.

Trial	Set-up	Ventilation, $m^3\ s^{-1}$	Inlet velocity, $m\ s^{-1}$	*Re*	*Rm*, $m^2\ s^{-2}$	TAN, $mg\ l^{-1}$	pH	Ammonia, $mg\ m^{-3}$	
								Inlet*	Outlet*
1	1	0.02	1	700	0.0044	23000	8.7	1.13 ± 0.08	46.17 ± 2.22
		0.04	2	1400	0.0175	23000	8.7	2.58 ± 0.20	33.74 ± 0.94
		0.06	3	2100	0.0394	23000	8.7	1.74 ± 0.12	27.71 ± 0.59
		0.08	4	2800	0.0700	23000	8.7	2.97 ± 0.05	23.93 ± 0.45
	2	0.02	1	700	0.0044	23000	8.7	2.58 ± 0.19	46.17 ± 2.22
		0.04	1	1400	0.0088	23000	8.7	2.97 ± 0.05	26.96 ± 1.23
		0.06	1	2100	0.0131	23000	8.7	2.15 ± 0.11	20.05 ± 0.85
		0.08	1	2800	0.0175	23000	8.7	2.20 ± 1.16	17.93 ± 0.74
2	1	0.02	1	700	0.0044	8400	9.0	0.94 ± 0.06	20.67 ± 0.98
		0.04	2	1400	0.0175	8400	9.0	1.08 ± 0.07	15.23 ± 0.65
		0.06	3	2100	0.0394	8400	9.0	1.02 ± 0.09	12.02 ± 0.35
		0.08	4	2800	0.0700	8400	9.0	1.16 ± 0.09	10.26 ± 0.30
	2	0.02	1	700	0.0044	8400	9.0	0.94 ± 0.06	20.67 ± 0.98
		0.04	1	1400	0.0088	8400	9.0	0.89 ± 0.13	13.03 ± 0.86
		0.06	1	2100	0.0131	8400	9.0	0.82 ± 0.08	9.76 ± 0.61
		0.08	1	2800	0.0175	8400	9.0	0.75 ± 0.07	8.57 ± 0.82
3	1	0.02	1	700	0.0044	6700	9.0	0.83 ± 0.07	17.25 ± 0.96
		0.04	2	1400	0.0175	6700	9.0	1.07 ± 0.12	12.67 ± 0.53
		0.06	3	2100	0.0394	6700	9.0	1.00 ± 0.08	9.83 ± 0.28
		0.08	4	2800	0.0700	6700	9.0	0.91 ± 0.10	8.02 ± 0.22
4	3	0.01	0.5	350	0.0012	6700	9.0	0.67 ± 0.07	22.47 ± 3.48
		0.02	1.0	700	0.0044	6700	9.0	0.83 ± 0.07	17.25 ± 0.96
		0.03	1.5	1050	0.0098	6700	9.0	0.95 ± 0.08	14.25 ± 0.73
		0.04	2.0	1400	0.0175	6700	9.0	1.07 ± 0.12	12.67 ± 0.53

* mean ± standard deviation.

where E is emission rate, mg $s^{-1}m^{-2}$; A_t is total inlet opening area, m^2 ; A_s is ammonia release surface area, m^2 ; C_o is outlet ammonia concentration, mg m^{-3}; C_i is inlet ammonia concentration, mg m^{-3}.

The average inlet velocities ranged from 1.0 to 4.0 m s^{-1} for most of the tests. Therefore, emission rate at the inlet velocity of 1 m s^{-1} was used as a base emission rate, a method successfully used by Smith and Watts (1994), to calculate the non-dimensional normalised emission rate (Eq. (11)) for model comparisons.

$$\text{Normalised emission rate} = \frac{E}{E_1} \quad (11)$$

where E_1 is reference emission rate at inlet air velocity of 1 m s^{-1} for the corresponding experiment set-up, mg s^{-1} m^{-2}.

The non-dimensional normalized return air velocity was calculated as

$$\text{Normalised return air velocity} = \frac{U_r}{U_i} \quad (12)$$

where U_r is the return air velocity, m s^{-1}.

4. Results and discussion

4.1. *Air flow pattern*

The smoke test of airflow patterns in the scale models showed that the supply air entering from the two side-wall inlets travelled horizontally until they met in the middle of the

Table 5 – Experimental conditions and test results in SM-2.

Trial	Set-up	Ventilation, $m^3\ s^{-1}$	Inlet velocity, $m\ s^{-1}$	*Re*	*Rm*, $m^2\ s^{-2}$	Ammonia, $mg\ m^{-3}$	
						Inlet*	Outlet*
1	1	0.005	1	350	0.0044	8.9 ± 0.2	27.2 ± 1
		0.010	2	700	0.0177	8.3 ± 0.1	21.5 ± 0.6
		0.015	3	1050	0.0399	8.5 ± 0.3	20.2 ± 1.1
		0.020	4	1400	0.0709	7.8 ± 0.1	16.9 ± 0.5
	2	0.005	1	350	0.0044	8.9 ± 0.2	27.2 ± 1
		0.010	1	700	0.0089	8.3 ± 0.1	21.1 ± 1
		0.015	1	1050	0.0133	8.5 ± 0.1	18 ± 0.5
		0.020	1	1400	0.0177	7.8 ± 0.2	15.9 ± 0.4

TAN = 5100 mg l^{-1}, and pH = 8.7. * mean ± standard deviation.

Table 6 – Regression equations of normalised emission rates (E/E_1) in the two scale models.

Parameter	Strategy	Model	E/E_1	R^2
Re	Constant inlet opening	SM-1	$0.0528R_e^{0.4513}$	0.9903
		SM-2	$0.0470R_e^{0.5238}$	0.9776
		SM-1 & SM-2	$0.1523R_e^{0.3194}$	0.6104
Re	Constant inlet velocity	SM-1	$0.1451R_e^{0.2917}$	0.9056
		SM-2	$0.0949R_e^{0.4047}$	0.9881
		SM-1 & SM-2	$0.3451R_e^{0.1853}$	0.3661
*Re**	Constant inlet opening	SM-1	$0.0371R_e^{0.5008}$	0.9999
		SM-2	$0.0470R_e^{0.5238}$	0.9776
		SM-1 & SM-2	$0.0421R_e^{0.5123}$	0.6279
Rm	Constant inlet opening	SM-1 & SM-2	$3.6837R_m^{0.2379}$	0.9713
	Constant inlet velocity	SM-1 & SM-2	$5.9370R_m^{0.3293}$	0.8299

*Used the same *Re* in the two scale models.

model before turning downwards and forming two cycles of opposite directions (Fig. 2a). The two contra-rotating flows were symmetric about the vertical centre line across the widths of the model. These ventilation air streams were in direct contact with the floor in the model (Fig. 1), which because the model did not have slatted floors was equivalent to pit manure level in pig houses. This symmetrical air flow pattern was similar to that achieved by Ye et al. (2009) and Zhang et al. (2008). Details of the air flow patterns depend on ventilation rate, inlet air velocity, and inlet opening height (Saha and Zhang, 2010). A linear correlation ($R^2 = 0.89$) between the inlet air velocity and the return air velocity was demonstrated in this study (Fig. 2b). A similar relationship was also found by Strom et al. (2002)in a full-scale room study. At constant inlet air velocity of 1 m s^{-1} but with different inlet opening height and ventilation rates, the return air velocities were different. Because the airflow patterns at the two sides of the ventilated enclosure were symmetrical, only the left side of the model was considered for the study of surface air velocity, ammonia emission, and similarity criteria.

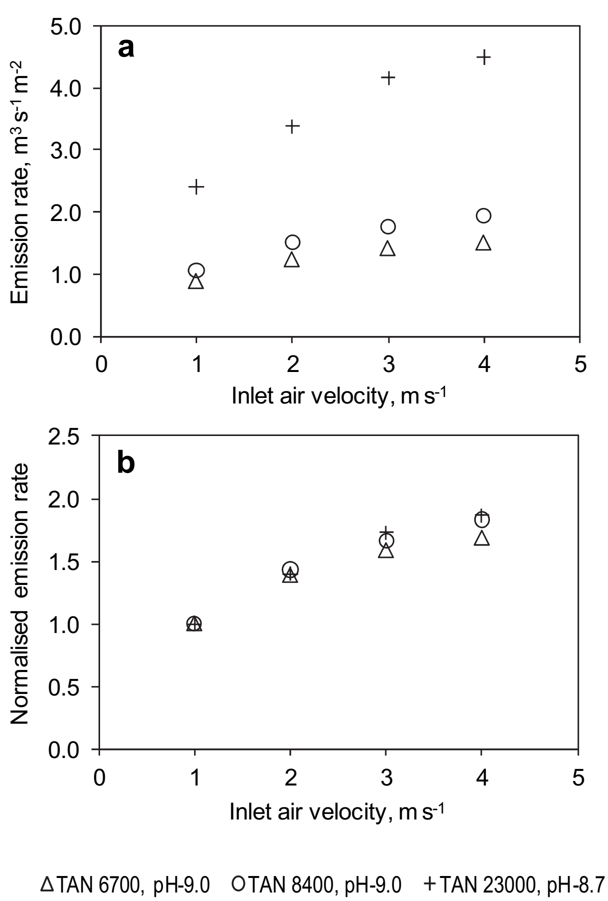

Fig. 3 – (a) Ammonia emission rate and (b) normalised ammonia emission rate at different inlet air velocities.

4.2. *Ammonia concentration*

An exhaust air temperature of 21.9 ± 0.25 °C was measured when the laboratory room air temperature was kept at 22.3 ± 0.28 °C; ammonia concentrations at the outlets varied and were correlated to the different TAN concentrations and pH values in the ammonia aqueous solutions among different trials and in SM-1 (Tables 4 and 5) and SM-2 (Table 6). Higher TAN in the solutions resulted in higher outlet ammonia concentrations (Table 5).

Ammonia concentrations at the outlets of scale models decreased as the ventilation rate increased due to the effect of dilution and flushing. This reduced concentration could increase the difference in partial pressures between the emission source and the ventilated air space. Partial pressure difference is the driving force for ammonia release from liquid solutions.

4.3. *Ammonia emission rate*

Ammonia emission rates increased as the inlet air velocities increased with all three different ammonia concentrations in aqueous solutions (Fig. 3a). Moreover, at the same inlet air velocities, ammonia emission rates were higher when the TAN concentrations were higher in the aqueous solutions. At the same pH in the aqueous solutions, a 25% higher TAN resulted in almost 25% higher emission rates (Fig. 3a). On the other hand, an aqueous ammonia solution with 23000 mg l^{-1} TAN and pH of 8.7 resulted in 2.8 times higher ammonia emission rate than the solution with 6700 mg l^{-1} TAN and pH of 9.0, though there was a 3.4-time difference between the two TAN concentrations. This indicated that pH value also affected ammonia emission rates. The higher the pH value, the more dissolved ammonia was in the solution and thus the higher concentration of gaseous ammonia was available at the solution surface. Ye *et al.* (2008) also confirmed that increased pH value of ammonia solution enhanced ammonia mass transfer rate.

The relationship between the emission-related variables was masked by large differences in the magnitude of emissions among the different trials. This problem was solved by using a non-dimensional emission rate as used by Smith and Watts (1994) who compared experimental results between two wind tunnels of different sizes. By considering ammonia emission rate at 1 m s^{-1} air velocity (E_1) as the base emission rate for prevailing conditions with the TAN and pH in aqueous solution, temperature, moisture content, and solution age, etc., the

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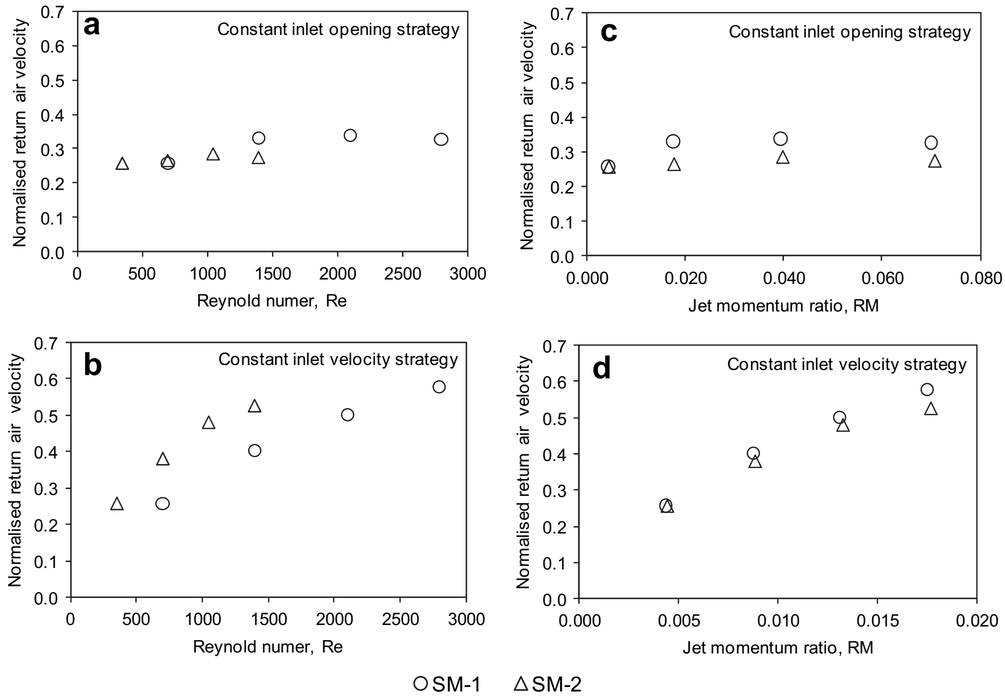

Fig. 4 – Comparison of normalised return air velocity based on *Re* and *Rm* at two ventilation control strategies.

non-dimensional normalised emission rates were similar at different air velocities, although the aqueous solution properties were quite different among the three experiments (Fig. 3b). If the relationship between the normalised emission rate and the air velocity shown in Fig. 3b assumed to be a power curve, then Eq.(11) can be written as:

$$\frac{E}{E_1} = 1.018U_i^{0.43} \ (R^2 = 0.98) \tag{13}$$

where R^2 is the coefficient of determination.

Compared with the work of Smith and Watts (1994), the ammonia emission rates in this study had two more dependent variables, the TAN and the pH in aqueous solution between the scale models. However, the experimental results shown in Fig. 3b demonstrated that the non-dimensional normalised emission rate could be a good tool to compare the similarity parameters *Re* and *Rm*.

4.4. *Comparison of similarity parameters* Re *and* Rm

4.4.1. *Return air velocity*

The normalised return air velocities calculated using Eq. (12) at constant inlet openings and constant inlet air velocities were compared with the *Re* and *Rm* and presented in Fig. 4. By keeping similar *Rm* in the two models in set-ups 1 and 2, the calculated *Re* values were from 700 to 2800 and from 350 to 1400 in SM-1 and SM-2, respectively (Table 2). In set-up 3, the *Re* range was 350–1400 for both models (Table 3). These results made it difficult to directly compare the normalised return air velocities for $Re > 1400$ (Fig. 4a and b). At the same inlet *Re*, the inlet air velocity was always lower in the SM-1 than in the SM-2. The return air velocities above the emission surface could be expected to be lower in SM-1 than SM-2 as the return air velocity was linearly correlated to the inlet air velocity. But at constant inlet opening, the normalised return air velocity above the emission surface was similar in the two models when using *Re* as a similarity parameter (Fig. 4a). This result was in line with the study of Yu and Hoff (1999). Additionally, Yu and Hoff (1999) found that air velocity profiles along the ceiling for a model and a prototype were not consistent with *Re* although the dimensionless peak air velocities between the model and the prototype were similar in the floor region. Using the constant inlet air velocity strategy, the normalised return air velocities were always higher in SM-2 than SM-1 at the same *Re* (Fig. 4b). At constant inlet air velocity but with different air inlet heights and ventilation rates in the scale models, the return air velocities above the emission surfaces were different.

When using *Rm* as the similarity parameter, the normalised return air velocities for SM-1 and SM-2 were similar for both ventilation control strategies, although some non-significant differences were observed at higher *Rm*, i.e., at higher inlet air velocities and larger inlet opening (Fig. 4c and d). These differences might be related with the higher h/H ratio in SM-1 than in SM-2.

4.4.2. *Ammonia emission rate*

The non-dimensional normalised ammonia emission rates increased as *Re* or *Rm* increased with both control strategies (Figs. 5 and 6). This was expected because gas emission rates are directly proportional to the surface air velocity in scale models studies (Saha et al., 2010; Ye et al., 2008). The normalised emission rates were higher in SM-2 than in SM-1 at the same *Re* values for both control strategies and at different

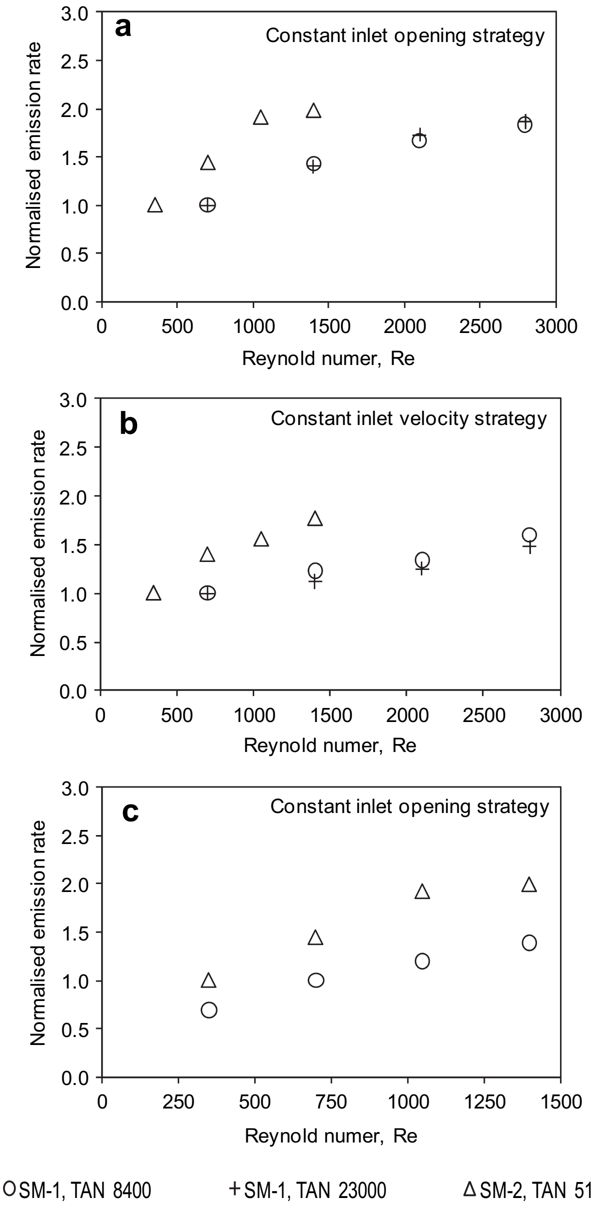

Fig. 5 – Comparison of normalised ammonia emission rate based on *Re* at three set-ups with two ventilation control strategies.

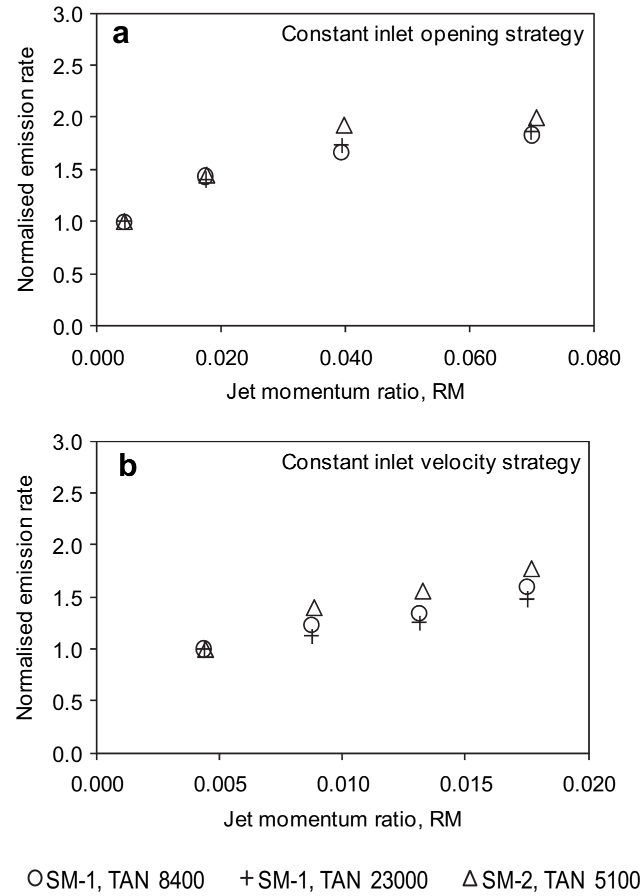

Fig. 6 – Comparison of normalised ammonia emission rate based on *Rm* at two ventilation control strategies.

TAN concentrations (Fig. 5a, b, and c). Air velocities in the air-jets were lower in SM-1 than SM-2 at the same *Re*, therefore reducing jet momentum, mass transfer, and normalised emission rate with SM-1 (Fig. 5c).

However, the plot of normalised emission rate against *Rm* (Fig. 6a and b) shows that the non-dimensional normalised emission rate was similar irrespective of the ventilation control strategies adopted with the models. This indicated that *Rm* was the preferable similarity parameter rather than *Re* in scale model studies for prototype emission rate estimation. The small differences found between the normalised emission rates with SM-1 and SM-2 were as expected because of the small differences in h/H ratio that resulted the differences in velocity distributions and turbulence scales in boundary layers.

The regression equations of normalised emission rates as functions of *Re* and *Rm* in Table 6 indicate that, when using *Re* as the similarity criterion, the differences between the two scale models within the same control strategy were significant. However, because the coefficient of determination (R^2) for each of the six single-model equations in Table 6 were high, the equations for a single scale model using *Re* can be applied to estimate the emission rate for individual models. The normalised emission rate did not correlate well between the two models in all strategies when *Re* was used as the similarity parameter. When *Rm* was used as the similarity parameter, the normalised emission rates between the two models were very close, demonstrating good correlations between the two scale models. Using constant inlet opening and constant inlet velocity control strategies, R^2 were 0.97 and 0.83, respectively. Therefore, *Rm* can be used as similarity parameter for comparing two model results or comparing model results with the prototype.

5. Conclusions

Comparisons of airflow and ammonia release in the two scale models revealed several characteristics in the model studies. Air streams were symmetric about the vertical centre line inside the models. A linear correlation (R^2 = 0.89) was established between the inlet air velocity and the return air velocity. Higher concentration and pH of the aqueous ammonia solution resulted in higher gaseous ammonia concentrations in the model outlets and ammonia emissions from the models. The non-dimensional normalised emission rate was shown to be a good tool to compare the similarity parameters *Re* and *Rm*.

Our study confirmed that *Rm* was the preferred similarity parameter rather than *Re* for modelling the airflow and non-dimensional ammonia emission rates at different experimental conditions, including two ventilation control strategies and different TAN and pH in ammonia solutions. This was demonstrated because when using *Rm* as the similarity parameter, the normalised emission rates between the two scale models had R^2 of 0.97 and 0.83 for constant inlet opening and constant inlet velocity control strategies, respectively.

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