PHD DISSERTATION

Precision Zone Ventilation Design and Application in Pig Housing

by Chao Zong

AARHUS UNIVERSITY

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Chao Zong

Aarhus University Department of Engineering, Denmark

AARHUS UNIVERSITY
DEPARTMENT OF ENGINEERING

River Publishers

ISBN 978-87-93237-31-5 (e-book)

Published, sold and distributed by:
River Publishers
Niels Jernes Vej 10
9220 Aalborg Ø
Denmark

www.riverpublishers.com

Preface

This thesis is submitted as a partial fulfilment of the requirements for the Doctor of Philosophy (PhD) degree at Graduate School of Science and Technology (GSST), Aarhus University, Denmark.

This thesis presents PhD research in the period between October 2011 and September 2014. The experiments were carried out at the Air Physics Lab (L38) and the Climate Lab (SB33), Research Centre Foulum, Tjele. The work was funded by China Scholarship Council (CSC: 2011635050), Department of Engineering and the project "*Optimization of pit exhaust ventilation for reducing ammonia and odour emission from pig building*".

This thesis is based on the work presented in published research articles and submitted manuscripts, which are entitled:

1. **Zong, C.**, Li, H., Zhang, G., 2014. Airflow characteristics in a pig house with partial pit ventilation system: an experimental chamber study. *To be submitted to a peer review journal*.
2. **Zong, C.**, Feng, Y., Zhang, G., Hansen, M.J., 2014. Effects of different air inlets on indoor air quality and ammonia emission from two experimental fattening pig rooms with partial pit ventilation system – Summer condition. ***Biosystems Engineering***, Vol. 122, P 163-173.
3. **Zong, C.**, Zhang, G., Feng, Y., Ni, J.-Q., 2014. Carbon dioxide production from a fattening pig building with partial pit ventilation system. ***Biosystems Engineering***, Vol. 126, P 56-68.
4. **Zong, C.**, Li, H., Zhang, G., 2014. Ammonia and greenhouse gas emissions from fattening pig house with two types of partial pit ventilation systems. *Submitted to a peer review journal*.
5. **Zong, C.**, Zhang, G., 2014. Assessment of RANS turbulence models to predict airflow and dispersion in an experimental chamber of pig house with partial pit ventilation system. To be *submitted to a peer review journal*.
6. **Zong, C.**, Zhang, G., 2014. Numerical modelling of airflow and gas dispersion in the pit headspace via slatted floor: Comparison of two modelling approaches. ***Computers and Electronics in Agriculture***, *In press.*

During this study, I spent two months in the Agricultural Air Quality Laboratory (PAAQL), Department of Agricultural and Biological Engineering, Purdue University, USA and learned skills on online measurement techniques, data analysis and agriculture engineering developments in USA. I attended one international conference (AgEng 2014, Zurich, Switzerland) and made one oral and two poster presentations.

In addition, the following publications were produced during the PhD period:

Journal articles:

1. Wu, W., **Zong, C.**, Zhang, G., 2013. Comparisons of two numerical approaches to simulate slatted floor of a slurry pit model – Large eddy simulations. ***Computers and Electronics in Agriculture*** 93, 78–89.
2. **Zong, C.**, Wu, W., Zhang, G., Shen, X., Ntinas, G., 2013. A case study of airflow patterns around an arched type agricultural building: Investigating mesh convergence of different turbulence models. ***Acta Horticulturae***, Vol. 1008, 69-76.
3. Shen, X., **Zong, C.**, Zhang, G., 2012. Optimization of sampling positions for measuring ventilation rates in naturally ventilated buildings using tracer gas. ***Sensors*** 12, 11966-11988.

Conference papers:

4. **Zong, C.**, Zhang, G., Rong, L., Li, H., 2014. Investigation on ventilation effectiveness in a full-scale model pig house with partial pit ventilation system. *Proceedings International Conference of Agricultural Engineering*, Zurich, Switzerland.
5. Zhang, G., **Zong, C.**, Bjerg, B., 2014. An engineering approach for effective cleaning of exhaust air from confined livestock production housing – A review of partial pit air exhaust techniques. *Proceedings International Conference of Agricultural Engineering*, Zurich, Switzerland.
6. Rong, L., Liu, D., Pedersen, E., **Zong, C.**, Zhang, G., 2014. Ammonia and methane emission from a hybrid ventilated dairy cow building in Denmark. *Proceedings International Conference of Agricultural Engineering*, Zurich, Switzerland.
7. **Zong, C.**, Zhang, G., 2013. Investigation of airflow characteristic around slatted floor in livestock building: A scale model study. *Precision Livestock Farming 2013: Papers presented of the 6th European conference on precision livestock farming*. 643-651.
8. Zhang, G., Kai, P., **Zong, C.**, 2013. Precision ventilation for optimal indoor air quality and reduction ammonia emission from pig production housing. *Precision Livestock Farming 2013: Papers presented of the 6th European conference on precision livestock farming*. 883-892.
9. Wu, W., Zhang, G., **Zong, C.**, 2012. Emissions of ammonia and greenhouse gases from two naturally ventilated barns for dairy cows. *ASABE - 9th International Livestock Environment Symposium 2012, ILES 2012*, Valencia, Spain.

Acknowledgements

I would like to acknowledge the following persons who have been involved in my PhD study in various manners.

My first and foremost thanks go to my supervisor, Dr. Guoqiang Zhang, Senior scientist in Department of Engineering, Aarhus University. His broad knowledge, expert guidance, continuous support, and enthusiastic attitude on science inspired me on my work, and motivated my progress academically and personally.

I express my great appreciations to the following people who used to work together with me in our research group: Dr. Wentao Wu, Dr. Xiong Shen, Dr. Li Rong, Dr. Georgios Ntinas, Mr. Ying Feng and PhD student Hao Li.

This PhD project would not have been possible without the assistance from lab technicians. I deliver my gratitude to the laboratory technicians Jan Ove Johnsen, Simon Kristensen and Jens Kristian Kristensen from Aarhus University.

I'd like to extend my thanks to Dr. Jiqin Ni from Purdue University, USA, for hosting my international stay there and instructive input on my PhD work. I'm grateful to the help from friends in USA during my stay there. Special thanks go to Andrew Mach and his family for their kindness and friendship.

I give much gratitude to my colleagues at Department of Engineering, Aarhus University; international friends used to live in the Nørresø Kollegiet; and all the Chinese friends in Foulum. Your faces of smile and acts of kindness made my PhD period filled with joy.

Finally, I am deeply indebted to my girlfriend Huiming Liu for her understanding, tolerance, patience and support. At the same time, I would like to give my sincere thanks to my parents and my sisters who support me all the time.

Chao Zong 宗超

October, 2014, @Foulum, Denmark

Abstract

Intensive pig production is an important source of polluting gaseous emissions in Denmark. Emissions of ammonia (NH_3) to the atmosphere cause soil acidification and eutrophication of aquatic ecosystems, while emissions of greenhouse gases (GHG) including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), are connected with global warming and climate change. To minimize their negative impacts on ecosystems and environments, the emissions have to be reduced.

Among various emission reduction techniques that under development, ventilation design and control is the basic approach under consideration. The ventilation system of animal houses can significantly influence local thermal conditions, indoor air quality and emission to the neighbouring atmosphere. A well designed, functional, and efficient ventilation system can drive fresh air into a building and remove airborne contaminants effectively. Aiming at effectively reduction of emissions and improving indoor air quality, a concept of precision zone ventilation including direct air supply system and partial pit ventilation (PPV) system and etc., was investigated in this thesis. The PPV system applies an additional pit exhaust extracting the most concentrated polluted air from the source zone.

The objectives of this thesis are to generate the knowledge of precision zone ventilation in pig production buildings, primarily the PPV system; to investigate airflow characteristics and effect of different air inlets and seasons on NH_3 and GHG in a pig unit with PPV; analyse the feasibility of numerical simulations to predict airflow and pollutant transportation in a pig unit with PPV; and assess the geometry simplification of modelling slatted floor.

Experimental investigations are carried out both in laboratory and field conditions. A climate chamber of pig production unit with PPV system was used to analyse the detailed airflow and dispersion inside the pig building. Three primary factors influencing the airflow characteristics were evaluated. Two trials of experiments in both summer and winter periods were carried out in an experimental fattening pig production house with PPV systems. Each trial covered an entire production period from 30-110 kg pig^{-1}. Concentrations and emissions of NH_3 and GHG were continuously measured. Performance of PPV system under field conditions was analysed. Computational fluid dynamics (CFD) is used to for computer modelling. The feasibility of steady Reynolds-averaged Navier-Stokes (RANS) turbulence models on predicting airflow and dispersion in pig building with PPV system was investigated through comparisons. At the end of this thesis, the uncertainty of modelling slatted floor as porous media in CFD was assessed.

The results of this PhD study demonstrate that partial pit ventilation is a reliable approach to mitigate emissions from mechanically ventilated pig housing and also provide reference for CFD simulations on pig building with PPV system.

Resumé på Dansk

Intensiv svineproduktion er en vigtig kilde til luftforurenende gasser i Danmark. Udledning af ammoniak (NH_3) til atmosfæren forårsager forsuring af terrestriske økosystemer og eutrofiering af akvatiske økosystemer. Kuldioxid (CO_2), metan (CH_4) og lattergas (N_2O) er drivhusgasser, der, udledt til atmosfæren, bidrager til den globale opvarmning og deraf afledte klimaforandringer. Det er nødvendigt at nedbringe emissionerne af disse gasser for at reducere deres negative miljø- og klimamæssige påvirkninger.

Ventilationsdesign og styring er blandt de mange miljøteknologier, som er under udvikling indenfor landbruget. Ventilationssystemet i stalde har stor indflydelse på staldenes lokal- og mikroklima, luftkvalitet og gasemissioner til atmosfæren. Et veldesignet, funktionelt og effektivt ventilationsanlæg kan effektivt fjerne luftbårne kontaminanter fra staldrummet og samtidig opretholde optimale temperaturforhold ved tilførsel af frisk udeluft.

Med henblik på at effektivt at reducere gasemissioner og forbedre luftkvaliteten i stalde blev et nyt ventilationskoncept baseret på præcisions-zoneventilation med lokal lufttilførsel og partiel kildeventilation, i det følgende benævnt PPV-system, behandlet i nærværende ph.d.-afhandling. PPV-systemet benytter sekundær ventilationsudsugning i gyllekanalerne med henblik på fjernelse af højforurenet luft direkte ved kilden.

Formålet med denne afhandling er at generere viden om præcisions-zoneventilation i svinestalde, primært PPV-systemet, specifikt ved at karakterisere luftstrømningerne som funktion af indretning af luftindtag / luftudsugning under varierende driftsbetingelser og betydningen for emissionerne af ammoniak og drivhusgasser i svinestalde med PPV-system; at anvende numeriske simuleringer til at forudsige luftstrømninger og transport af forureningsgasser i en svinestald etableret med PPV-systemet samt; at vurdere metoder for geometrisk simplificeret modellering af spaltegulve i CFD.

Eksperimentelle undersøgelser blev gennemført i laboratoriet såvel som i fuld skala. En forsøgssvinestald etableret med PPV-systemet blev anvendt til at foretage studier af luftstrømningers fordeling og gas transport i stalden. Effekten af tre primære faktorer, som påvirkede luftens strømningsprofil, blev undersøgt. To eksperimenter under hhv. sommer- og vinterforhold blev gennemført i en testsvinestald, der var udstyret med et PPV-system. PPV-systemets performance blev undersøgt under praksisnære driftsforhold omfattende en fuld slagtesvine-vækstperiode fra 30 til 110 kg levendevægt. Koncentrationer og emissioner af ammoniak og drivhusgasser blev fastlagt.

CFD (Computational fluid Dynamics) simuleringer blev benyttet til numeriske analyser af luftstrømningerne. Specifikt anvendtes Steady Reynolds Averaged Navier-Stokes (RANS) turbulensmodeller til at simulere luftstrømninger i stalde. I afslutning af afhandlingen en vurdering af usikkerheden af CFD-simulering af luftstrømninger i stalde, hvor arealer med spaltegulv modelleres som "porous media", er gennemføret.

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Chapter 1

General introduction

1.1.Negative impacts from pig production

For more than 100 years, the pig production has been an important asset for Denmark, which contributes substantially to the economics both in terms of employment and export. In order to maintain or get a higher profit, the trend in Danish pig production is moving towards fewer numbers of pig farms but larger scale and intensive farms. At the same time, intensive pig production is under more pressure and some structural improvements are expected in the near future due to environmental issues caused by pig farming.

Pig production in Denmark is a great source of ammonia (NH_3) and greenhouse gases (GHG) emissions, which have a series of negative impacts on surrounding environment and climate (Cabaraux et al., 2009; Hutchings, Sommer, Andersen & Asman, 2001; Philippe, Laitat, et al., 2011).

It is well known that NH_3 is a toxic gas, which has potential health hazards to both human beings and animals inside the animal house (Banhazi, Seedorf, Rutley & Pitchford, 2008; Donham, 1991). Meanwhile, emissions of NH_3 to the atmosphere can affect large scale of ecosystem by creating soil acidification and aquatic eutrophication (Krupa, 2003). It has been reported that almost 99% of the total NH_3 emissions in Denmark were originated from agricultural sources, in which emissions from pig housing accounted for 34% of agricultural section (Hutchings et al., 2001). Due to its severe impacts, ammonia has always been given the most attention as the key air pollutant.

Greenhouse gases, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), are related to global warming and climate change. CO_2 originates from both animal respiration and manure in livestock buildings. The amount of CO_2 production has been commonly used for ventilation rate estimation (Feddes & DeShazer, 1988). CH_4 and N_2O contribute significantly to greenhouse effect as their global warming potential (GWP) over a 100-year period are, respectively, 25 and 298 times that of CO_2 (Intergovernmental Panel on Climate Change, 2007). In addition, N_2O also gives rise to the loss of the ozone layer.

Reducing NH_3 and GHG emissions have been an important goal by national and international regulations for a long term (United Nations Economic Commission for Europe, 2013). Ammonia emission in Denmark got reduction from 109,900 tonnes NH_3-N per year to 80,400 tonnes NH_3-N per year from 1990 to 2004. The 1999 Gothenburg Protocol required Denmark to abate the emission to 56,800 tonnes NH3-N/year by 2010. A further reduction to 53,200 tonnes/year is expected in the new projection of ammonia emission in Denmark from 2005 until 2025. It is assumed that techniques for eliminating NH_3 emissions can reduce emissions of other gaseous contaminants as well.

In a livestock building based on slurry, the sources of NH_3 are the soiled solid floor, slats, side-wall of the slurry pit, and the surface of the slurry under the slatted floor (Fig. 1) (Sommer et al., 2006). Sommer et al. (2006) proposed to split the housing compartment into NH_3 emission elements typical for each emitting surface to calculate NH_3 emissions from different housing types, as the physics and chemistry of sources of NH_3 may differ.

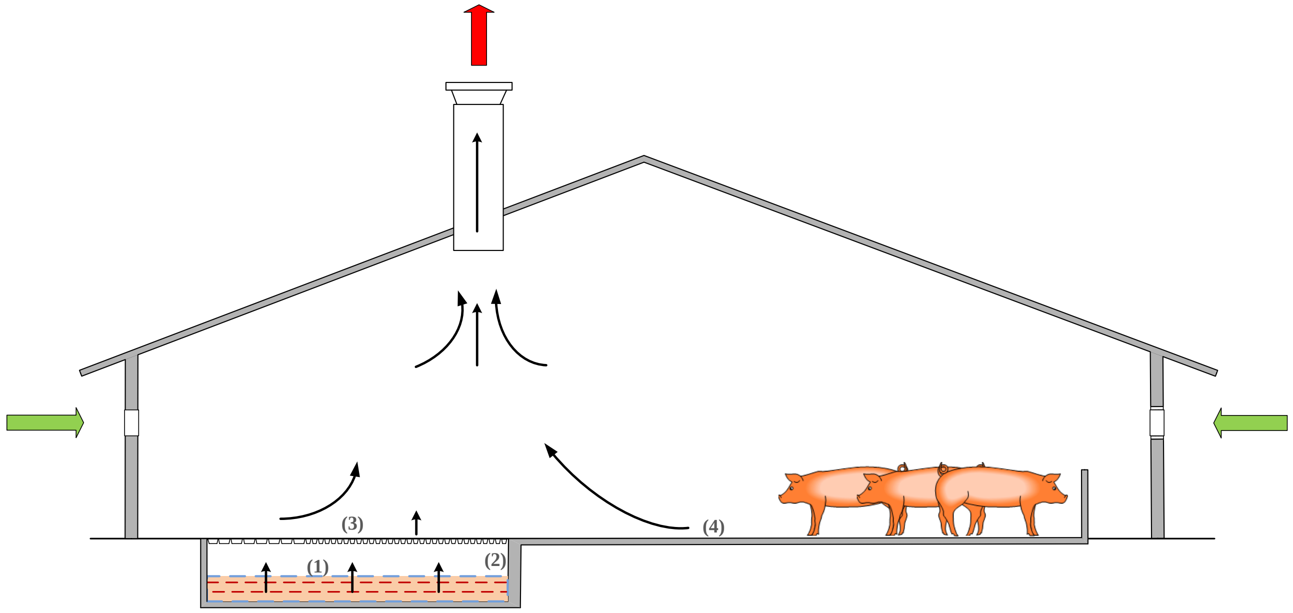

Figure 1.1 - Emission sources from a typical fattening pig house. The emission of gases from the house is given by the sum of emission from each source in the animal house: (1) slurry surface, (2) soiled side-walls of slurry pit, (3) slatted floor above the slurry pit, and (4) soiled solid floor.

Gaseous formation and volatilization can be influenced by many different factors: animals, (e.g. genetics, diet, number and weight, animal activity, and behaviour), animal wastes (e.g. storage methods, treatment, pH, temperature, and surface area), ventilation (control strategy, temperature, flow rate, and air velocity above manure surface) and other site-specific factors (Blanes-Vidal, Hansen, Pedersen & Rom, 2008; Haeussermann, Hartung, Gallmann & Jungbluth, 2006). An optimal control of those influencing factors can help to reduce gaseous emissions from livestock productions.

1.2. Ventilation systems design for improving climate and environment of pig housing

The ventilation system of animal houses is important in livestock production due to its significant influence on local thermal conditions and indoor air quality. A well designed, functional, and efficient ventilation system can drive fresh air into a building and remove airborne contaminants effectively. Inefficient ventilation is harmful to the health and productivity of animals, as well as the health of workers. A poorly designed ventilated facility has a large potential for wasting energy.

According to the type of driving force employed, ventilation systems in livestock buildings may be grouped into natural or mechanical ventilation systems. Mechanical ventilation has been considered as the most effective technique for indoor climate/environment control, particularly for animals with a narrow productive temperature range, since it offers a direct method of regulating the indoor environment by altering the velocity and temperature and moisture properties of the incoming air (Norton, Sun, Grant, Fallon & Dodd, 2007).

In Denmark, negative pressure ventilation systems with roof exhaust units combined either diffuse ceiling inlet or flap inlet (wall or ceiling flap) are conventionally used in pig housing. Since last decade, ventilation system with diffuse ceiling inlet have become popular for its low investment costs as well as lower supply air velocity which can prevent cold air draft in the animal occupied zone (AOZ) compared with system with flap inlet. However, it also needs more energy to create a larger pressure difference between inside and outside of the building, primarily during summer. Crucially, the air speed is not high enough when it reaches the AOZ which causes a poor efficient convection heat removal for the animals in hot weather. Therefore, in some practices, ceiling mounted flap inlets are applied to increase air velocity in animal zone. In general, ventilation systems are designed to provide perfect mixing of the supply air with the room air to ensure uniform conditions in the entire room (Barber & Ogilvie, 1982; Zhang, Morsing & Strom, 1996). Meanwhile, the dispersion of ammonia and other contaminants are mostly affected by airflow inside the livestock building (Zhang & Strom, 1999). The animal house with a high concentration of gases and odours in room air cannot be controlled effectively by a conventional ventilation system with only roof or ceiling exhaust units, especially during winter as the minimum ventilation rates employed (Pohl & Hellickson, 1978).

A very high efficient way using mechanical ventilation to eliminate those polluted gaseous is the employ of air purification system (e.g. air scrubber) at air exhausts (Philippe, Cabaraux & Nicks, 2011; Zhao, Aarnink, de Jong, Ogink & Koerkamp, 2011; Zucker, Scharf, Kersten & Müller, 2005). However, it is quite expensive because of high investment and operation costs related to energy, chemical and filter consumption and maintenance for both ventilation and purification systems (Melse, Ogink & Rulkens, 2009). One proposed strategy to reduce the costs is cleaning only a partial amount (10% of maximum ventilation rate) of exhaust air extracted from the main source zone where highly concentrated air pollutants originate from (Saha, Zhang, Kai & Bjerg, 2010; Zong, Feng, Zhang & Hansen, 2014). A partial pit ventilation (PPV) system with an extra pit exhaust under slatted floor has therefore been developed. Besides, employing a PPV system could remove the gases and odours from the pit space above the manure surface before convection airflow and turbulences transfer the gases up to the room space, and significantly improve indoor air quality (Saha et al., 2010). And consequently both working environment and animal welfare are also improved.

Precision zone ventilation, consisting of direct air supply into the AOZ and precision exhaust ventilation from the pollution source zone and etc., may provide more efficient climate control and improved air quality. According to the literature, the scientific knowledge is still lacking for correct modelling, design and control of a system with precision zone air supply as well as exhaust in pig housing. Therefore, research on the issue regarding experiments and mathematical modelling is essential.

1.3. Modelling mechanically ventilated pig housing

Computational fluid dynamics (CFD) is a powerful tool which can calculate both spatial and temporal aspects of fluid pressure, temperature and velocity, and has been commonly used to predict airflow pattern as well as contaminant distribution in ventilated room spaces. CFD uses numerical methods and algorithms to solve and analyse problems that involve fluid flow, heat and mass transfer, phase change, chemical reaction, mechanical movement, and solid and fluid interaction. The fundamental basis of almost all CFD problems is the Navier–Stokes equations, which are the governing equations of fluid flow and heat transfer.

As the ubiquitous nature of fluids and same governing equations of fluid dynamics, there has been widespread application of CFD in many disciplines. In recent years, CFD has been proved useful in simulations of livestock building in predicting aspects occurring in many types of systems. The first CFD study on livestock buildings was conducted by Choi et al. (1988), with geometry crudely approximated as a two-dimensional rectangle. Afterwards, more work was done in developing more complicated and accurate CFD models for simulating livestock buildings (Zhang et al., 2000). For pig productions facilities, many of the CFD applications been conducted towards optimising environmental conditions (Bjerg, Zhang & Kai, 2008a, 2008b, 2011; D. Sun, 2002; H. W. Sun, Keener, Deng & Michel, 2004). These studies can be effectively grouped into the modelling of pollutant dispersion and the thermal environment.

In a livestock building with a slatted floor system, pollutants like ammonia and odours are mostly emitted from the zone near the slatted floor, either the floor surface or the slurry pit under the floor (Saha et al., 2010; Ye, Zhang, Li, Strøm & Dahl, 2008; Zong et al., 2014). Airflow patterns in the pit headspace and air exchange between pit and room space can significantly affect the ammonia dispersion which will further affect indoor air quality and emissions from the building (Zhang & Strom, 1999). Detailed knowledge of the characteristics of airflow and mass transport under the slatted floor is the key part to predict the gas emission from the slurry pit.

A number of experimental and numerical studies have been performed on the flow and transport of pollutants in livestock buildings, but very few studies on modelling pit headspace under the slatted floor are available in the literature. A challenge of modelling pit headspace is how to treat the slatted floor. The slot width in a real livestock building is up to 0.02 m while the building dimensions can be several thousand times bigger. The big size difference between slot width and building dimensions prevents a direct modelling as it will create large number of meshes. The larger number of meshes of the geometry will require longer time to iterate the calculation. Due to the limited computer capacity and time consumption, geometry simplification is necessary when modelling livestock buildings with slatted floor. Porous media was therefore proposed to tackle this problem in modelling slatted floor (Bjerg et al., 2008a, 2008b; H. W. Sun et al., 2004; Wu, Zhai, Zhang & Nielsen, 2012). Nevertheless, the uncertainties of using porous media to simulate the slatted floor have not been well documented, especially comparing with measured data. For mechanically ventilated pig buildings with side wall air inlet, the dominant return airflow near the floor surface often has a direction perpendicular to the slat orientation (Zong et al., 2014). Investigations of modelling the slats orientated perpendicular to the flow direction should be carried out.

1.4.Research objectives

Removing the heat and pollutants directly at the sources will reduce the need for ventilation capacity, and result in reduced energy consumption and emission of ammonia and odours. Direct air supply into the animal occupied zone (AOZ) will provide effective thermal control and better welfare for animals during warm weather, especially for a system with only diffuse ceiling inlets. Precision partial source zone ventilation directed at the manure pit, with only a part of the total ventilation capacity, will yield a high effectiveness of the air purification process. Cleaning only the partial exhaust air from the ventilated building, the requirement of the airflow capacity for the cleaning unit will be reduced. Furthermore, it will reduce the spreading of airborne pathogens between pens.

Thus, the specific objectives of the PhD study come to:

(1) generate knowledge on applying precision zone ventilation in pig buildings, primarily the partial pit air exhaust ;
(2) investigate airflow characteristics in a model pig unit with partial pit ventilation affected by different ventilation rates, air inlets, slatted floor openings;
(3) investigate effects of different air inlets and seasons on ammonia and greenhouse gases concentrations and emissions from a pi house with partial pit ventilation;
(4) analyse the feasibility of using CFD to predict airflow and pollutant transportation in a pig unit with partial pit ventilation system;
(5) develop a method for the geometry simplification of modelling slatted floor (treating it as porous media), and assess its uncertainty.

1.5.Outline of this thesis

The starting point of the research topic was to generate fundamental knowledge of precision zone ventilation in livestock production buildings to achieve more effective ventilation and improved indoor air quality as well as reducing the required capacity of air cleaning devises. CFD methods were utilized to analyse and optimize the system configurations including inlet and floor type and the distribution of exhaust openings in the pen. Airflow characteristics in an experimental ventilation chamber of pig unit with a partial pit ventilation system were investigated (Chapter 2). Two trials of experiments including both summer and winter periods were carried out in an experimental fattening pig production unit with partial pit ventilation systems. Concentrations and emissions of ammonia and greenhouse gases were measured continuously and analysed. Effects of different ventilation configurations and seasonal variations on gaseous concentrations and emissions were investigated (Chapter 3, 4, 5). Later investigations were carried out using CFD simulations (Chapter 6, 7). The feasibility of CFD predicting airflow and dispersion of aerial contaminants was studied by Reynolds-averaged Navier-Stokes turbulences models (Chapter 6). The technical issue on simplifying the slatted floor in geometry should be solved before simulations of full scale building. The uncertainty of modelling slatted floor as porous media was therefore assessed (Chapter 7). The final chapter (Chapter 8) summarized the main findings of the thesis, and makes recommendations for future research.

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Chapter 2

Airflow characteristics in a pig house with partial pit ventilation system: an experimental chamber study

Paper I:

Zong, C., Li, H., Zhang, G., 2014. **Airflow characteristics in a pig house with partial pit ventilation system: an experimental chamber study**. Prepared submitting to a peer review journal.

Abstract

A partial pit ventilation system (PPV) has been proved capable to significantly improve indoor air quality and reduce ammonia emission if combined with an air purification system in field studies. The removal efficiency of PPV is very much airflow pattern dependent but research on detailed airflow characteristics in a room with this ventilation system is still missing. In this study, experiments were performed to investigate the influences of two types of air inlet, three types of floor and four levels of ventilation rate on airflow air velocities, turbulence intensities and airflow patterns near the floor region and air exchange rate between room and pit spaces. Results show that higher ventilation rate induced higher near-floor air velocity and higher air exchange rate in the pit. Much higher air velocities and lower turbulence intensities occurred in ventilation system with wall jet inlet (system-W) than in the one with diffusion ceiling inlet (system-C). A big dominant return flow was found in system-W, while small turbulent flows were in system-C. Increasing the floor opening ratio enhanced the air exchange rate between room and pit spaces. Results for ammonia emission from a field study regarding PPV together with different air inlets can be comprehensively explained by using the results of this study.

Keywords: *partial pit ventilation system, airflow, ventilation rate, floor type*

2.1. Introduction

Ammonia (NH_3), dust and odour emitted from livestock production system may lead to poor indoor air quality and cause negative impact to neighbouring environment. The release and dispersion of those airborne pollutants was highly affected by air movements inside the animal building (Morsing, Strom, Zhang & Kai, 2008). Effective and practical approaches to guide the airflow for reduction of those gaseous emissions from livestock buildings are highly desired. To develop the approaches, information of airflow characteristics is the first key step.

Many different factors can influence the airflow characteristics in animal houses. Those factors are mainly related to: locations of air inlets and outlets (Pohl & Hellickson, 1978), ventilation rate (Strom, Zhang & Morsing, 2002), inlet air-jet momentum (Zhang et al., 2008), floor design (Aarnink, Swierstra, Van Den Berg & Speelman, 1997; Morsing et al., 2008), manure depth (Buiter & Hoff, 1998; J. Q. Ni, Vinckier, Coenegrachts & Hendriks, 1999), heat produced by the animals (Morsing, Zhang, Strom, Bennetsen & Ravn, 2004; Zhang, Svidt, Bjerg & Morsing, 1999), and other site-specific factors. Scale model studies are popular in the investigations of airflow characteristics since the experiment condition can be easily controlled and model experiment costs much less compared with field experiment.

In Denmark, mechanical ventilation system with only roof or ceiling mounted exhaust units has been applied in pig production for many years. However, this conventional ventilation system has disadvantages of ineffective control of indoor air quality and gaseous emissions (Pohl & Hellickson, 1978; Saha, Zhang, Kai & Bjerg, 2010; Zong, Feng, Zhang & Hansen, 2014; Zong, Zhang, Feng & Ni, 2014). In order to improve the control efficiency, applying an extra pit ventilation system near the pollutants source zone has been proposed (Vantklooster, Roelofs & Gijsen, 1993). High concentrated airborne pollutants from the pit and soiled floor can be extracted directly *via* pit air exhaust to the air cleaning systems.

Studies on airflow characteristics in animal building with fully pit ventilation have been investigated in scaled models. Ross, Aldrich, Younkin, Sherritt, and McCurdy (1975) found that tapered exhaust ducts equipped with variable speed fans resulted in acceptable air distribution and temperature control, but unsatisfactory odour control in a pig structure. Pohl and Hellickson (1978) investigated the performance of five types of pit ventilation systems in a 1/12 size scale model swine finishing building and found cantered duct pit ventilation system created the best ventilation characteristics e.g. air velocity distribution and airflow patterns. Buiter and Hoff (1998) compared the effects of slurry pit management on NH_3 distribution using a one-half scale model with pit ventilation, and found manure depth significantly affected NH_3 emission and gas distribution in the pit headspace under the slatted floor. It was found that fully pit ventilation system can improve the indoor air quality, but increased total emission in the same time. When exhaust air from animal building is further treated by air cleaning devices (e.g. air scrubber), it will be quite expensive due to the required capacity, high consumption of energy, chemical and filter for a full pit ventilation system (Zong, Feng, et al., 2014).

To reduce the cost for air cleaning, partial pit ventilation (PPV) system was developed accordingly, which extracted only a partial amount (10%) of the maximum ventilation airflow rate from pit exhaust. The PPV system has been investigated in field conditions and have been proved to get remarkable indoor air quality improvement and emission reduction with only a small portion of exhaust air been purified (Saha et al., 2010; Ye, Saha, et al., 2009; Zong, Feng, et al., 2014). However, up to date, research on detailed airflow characteristic is still insufficient in a pig room with a PPV system. Knowledge on the airflow characteristics in the pig room with partial ventilation system, especially near the pollutant source zone, is useful for understanding the mechanisms of pollutants transport for further applications.

The objective of this study was to investigate how the airflow characteristics near the pollutants source zone affected by different types of air inlets, ventilation rates, and slatted floor openings, and to provide useful information to explain the NH_3 emission results reported by Zong, Feng, et al. (2014), which conducted in an experimental facility with living pigs.

2.2. Materials and methods

Experiments were conducted in the Air Physics Lab, Research Center Foulum, Aarhus University, Denmark.

2.2.1. Experimental set-up

2.2.1.1. Experimental chamber of pig house

An experimental ventilation chamber with inside dimensions of 4.47 m × 1.17 m × 2.89 m ($L \times W \times H$) was built as a sub-section of a fattening pig house which corresponded to a full scale pig pen with half width (Fig. 2.1). The front panel of the chamber was made of transparent glass, and the back and side panels were made of plywood which were painted in dark color for facilitating velocity measurements and visualization of airflow patterns with illuminated smoke (Fig. 2.2). The chamber was divided into two spaces by floor. The room space was above the floor with a height of 2.375m. The pit headspace under the floor was 0.515 m in height.

2.2.1.2. Ventilation systems

The experimental chamber was equipped with a negative pressure ventilation system, which was commonly applied in pig production housing in Denmark. There were two types of ventilation configurations in this study. Both configurations had the same layout of exhaust units: each with a partial pit exhaust and a sidewall room exhaust (Fig. 2.1). Room exhaust was a sealed iron pipe outlet with a diameter of 200 mm installed on the left wall (Fig. 2.1), which was the major air outlet. The pipe was connected *via* a flexible duct to a channel fan (Lindab type VBU 200B, Denmark) discharging the air to outside. Pit air was extracted by another type of fan (Lindab type VBU 100B, Denmark) *via* a 110 mm-diameter pipe outlet installed in the left wall just beneath the floor. The designed capacity of ventilation rate (VR_c) was 800 m^3 h^{-1}. The pit ventilation rate (VR_p) was set as 10% of VR_c during the experiment. Meanwhile, four levels of room ventilation rates (VR_r) were used in the experiment, which was 30%, 50%, 70% and 90% of the VR_c, respectively.

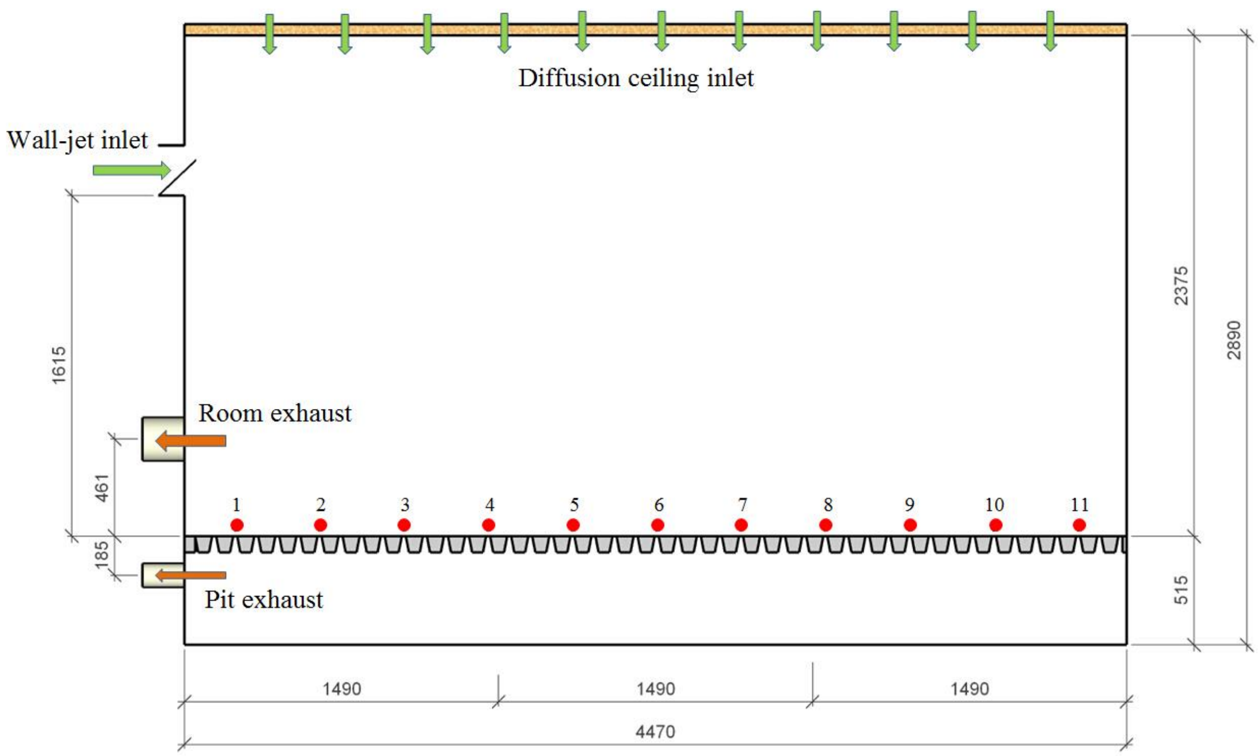

Fig. 2.1 - Layout of the experimental climate chamber of pig house with measuring points (red circle): number 1 to 11. All dimensions are in mm. Measurement locations were 40 mm above the floor surface.

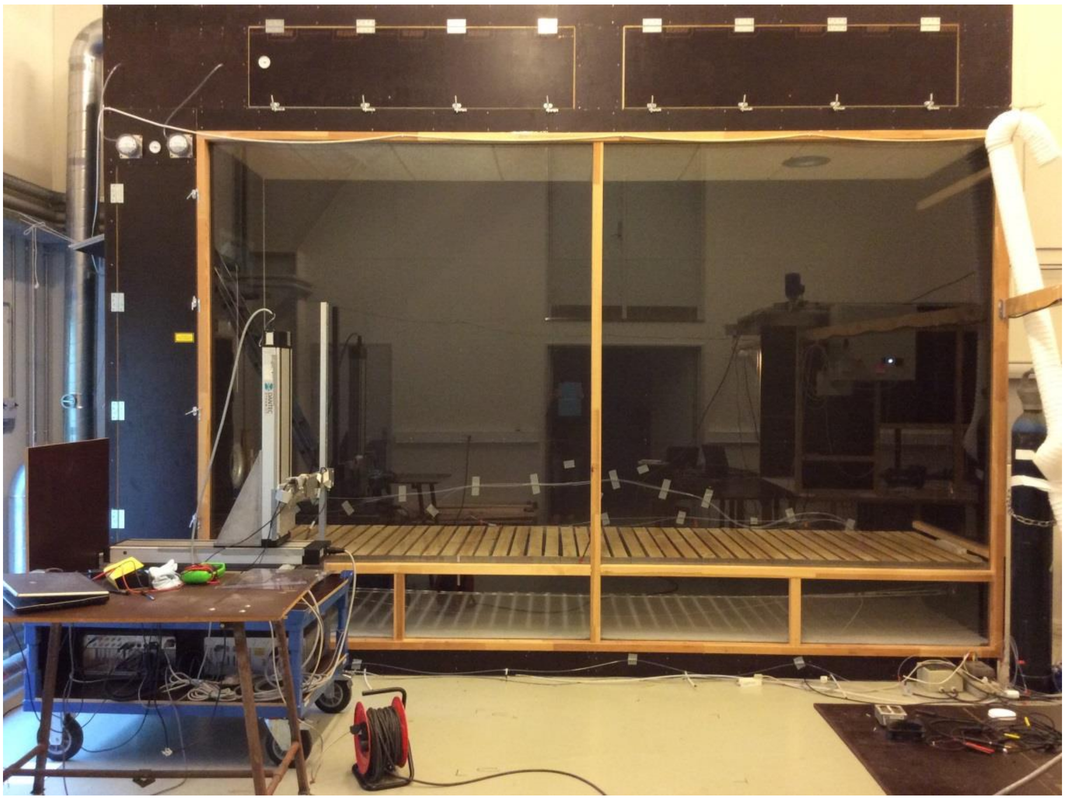

Fig. 2.2 - Experimental climate chamber of pig house and 2-D Laser Doppler Anemometer.

The only difference between the two configurations was the type of air inlets. One configuration was equipped with wall jet air inlet (system-W) while another had ceiling diffusion (system-C).

System-W was operated with wall jet air inlets plus partial pit ventilation system (Fig. 2.1). An adjustable flap wall-jet air inlet was installed on left side wall beneath the ceiling. The wall jets were placed 1.62 m above the floor, and in the symmetrical plan of the pig pen. The opening of wall jet air inlet was regulated together with room exhaust ventilation rates and the pressure difference (ΔP) between inside and outside of the chamber. To ensure the inlet air speed strong enough to reach the animal occupied zone (AOZ), the ΔP is usually kept at a certain range. In this study, the ΔP was kept approximately at 10 Pa.

System-C was equipped with diffusion ceiling air inlets plus partial pit ventilation system (Fig. 2.1). Two openings of 0.5 × 2.0 m located above the ceiling allowed fresh air to enter the attic of the chamber (Fig. 2.1a). The ceiling was made of porous materials which consisted of compressed straw plate and mineral wool isolation layer. It could diffuse supplied air from the attic into the enclosure chamber under negative pressure.

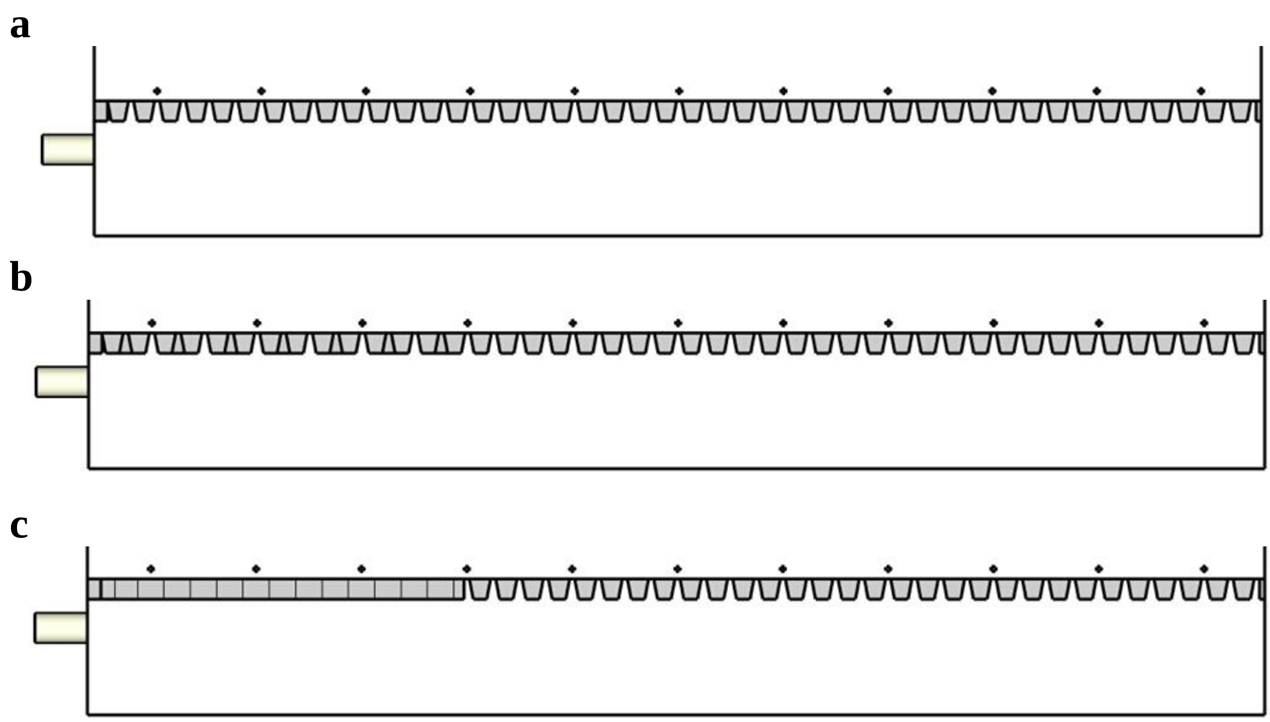

Fig. 2.3 - The three types of floor system: (a) fully slatted floor; (b) 1/3 drain floor + 2/3 slatted floor; (c) 1/3 solid floor + 2/3 slatted floor.

2.2.1.3. Floor types

Following the general practice of pig production and regulations for pig buildings with slatted floor in Denmark, the openings of slatted floor are varied in between 10 and 40%, as related to different production systems (Jensen & Hansen, 2006). Fully slatted floor was a traditional type floor commonly applied in Danish pig production. However in recent years, to improve the animal welfare, fully slatted flooring is no longer permitted in new installations. New floor systems bearing pigs' comfort in mind has been developed (Danish agriculture & Food Council, 2010). As a result, partially slatted floor with either partly drain or solid floor becomes popular in Denmark. The drain floor was a type of slatted floor with smaller slot opening. To determine the influence of different slatted floor types on air velocity, turbulence level and airflow pattern near the floor area and consequently to the emission rate from slurry under the floor and mass transport in pit head space, three types of slatted floor were investigated (Fig. 2.3). The three investigated slatted floor types are: (1) fully slatted floor (FS); (2) 1/3 drain floor + 2/3 slatted floor (DS); (3) 1/3 solid floor + 2/3 slatted floor (SS). The floor was made of wood with iron supports on both side edges. The feature of these investigated types of floor is listed in Table 2.1. The floor opening ratio is defined as the ratio of floor opening area to the total floor area.

Table 2.1 - Feature of three types of floor systems

Floor type	Opening ratio			
	Slatted floor	Drain floor	Solid floor	Average of the whole floor
Fully slatted floor	0.19	-	-	0.19
1/3 drain floor + 2/3 slatted floor	0.19	0.095	-	0.16
1/3 solid floor + 2/3 slatted floor	0.19	-	0	0.13

2.2.2. Measurement

Measurements were carried out under isothermal conditions (Fig. 2.1). The design of experiment included two types of air inlet, three types of floor and four ventilation rates. The three influence factors resulted in a total of 24 experimental runs. The experimental treatments are shown in Table 2.2. In addition, Table 2.3 demonstrates the airflow characteristics and settings for air inlets of both system-W and system-C.

2.2.2.2. Ventilation rate

Lindab FMU/FMDRU 200-160 and FMU/FMDRU 100-80 orifices (Denmark) was used to measure the room and pit ventilation airflow rate, respectively. The accuracy of the flow measuring method is 5-10% depending on the distance to the flow disturbance. The ventilation flows in the duct was determined using the equations:

$$VR_r = 105.84\sqrt{\Delta P_o} \quad (1)$$

$$VR_p = 26.35\sqrt{\Delta P_o} \quad (2)$$

where *VR* is ventilation rate, $m^3\ h^{-1}$; ΔP_o is pressure difference between upstream and downstream side of the orifice, Pa. The pressure differences were measured using a TSI pressure probe (Model 9596, TSI, USA) with an accuracy of $\pm 0.7\%$.

2.2.2.1. Air velocity, turbulence intensity and airflow pattern

A two-dimensional Laser Doppler Anemometer (LDA) (DANTEC, Skovlunde, Denmark) was used to measure air velocity and turbulence intensity (Ti) at the sampling positions along the floor surface with numbers from 1 to 11 (Fig. 2.1). Each point was measured 10 min. The Ti which defined as the ratio of the root mean square value of the velocity fluctuations to the mean velocity is a parameter to describe the level of turbulence in airflow.

Airflow patterns were observed using smoke from a smoke machine (Z-series II, Antari Ltd., Taiwan) and a laser sheet, which could provide a visualization of the path of airstreams.

2.2.2.3. Environmental parameters

The temperature and relative humidity of air which entered into the climate chamber was kept stable. The type T thermocouples connected to a data logger (Eltek Ltd, England) were used to measure inlet air temperatures. Relative humidity and temperature were regularly checked using a Veloci Calc multifunction velocity anemometer (Model 9565, TSI Inc., USA).

Table 2.2 - Experimental treatments

Air inlet types	Floor types	Ventilation rate settings		
		Pit ventilation rate, m h^{-1}	Room ventilation rate, m h^{-1}	VR_r/VR_c [a], %
Wall-jet air inlet	Fully slatted floor	80	720	90
	1/3 drain floor + 2/3 slatted floor	80	560	70
	1/3 solid floor + 2/3 slatted floor	80	400	50
		80	240	30
Diffusion-ceiling air inlet	Fully slatted floor	80	720	90
	1/3 drain floor + 2/3 slatted floor	80	560	70
	1/3 solid floor + 2/3 slatted floor	80	400	50
		80	240	30

[a] VR_r/VR_c is the ratio of room ventilation rate to the designed capacity of ventilation rate, which is 800 m^3 h^{-1} in this study.

Table 2.3 - Airflow characteristics in the air inlets of the climate chamber

Total ventilation rate, m^3 h^{-1}	VR_r/VR_c [a], %	ACH [b]	Wall-jet inlet				Diffusion-ceiling inlet		
			Inlet air velocity, m s^{-1}	Inlet Re	J [c]	ΔP, Pa	Inlet air velocity, m s^{-1}	Inlet Re	ΔP, Pa
320	30	21.3	2.62	18118	0.0016	9.4	0.017	8165	10.3
480	50	31.9	2.83	27177	0.0026	9.5	0.026	12247	15.4
640	70	42.5	3.15	36236	0.0038	10.1	0.034	16329	21.1
800	90	53.2	3.27	45295	0.0049	9.9	0.043	20412	26.9

[a] VR_r/VR_c is the ratio of room ventilation rate to the designed capacity of ventilation rate, which is 800 m^3 h^{-1} in this study.
[b] Air exchange rate.
[c] Jet momentum number as proposed by Barber and Ogilvie (1982).

2.3. Results

2.3.1. Air velocity

The vertical air velocities near the floor region along the length of climate chamber are summarized in Fig. 2.4. The two types of air inlets with different floor types under varied ventilation rates induced different profiles of vertical velocities near floor.

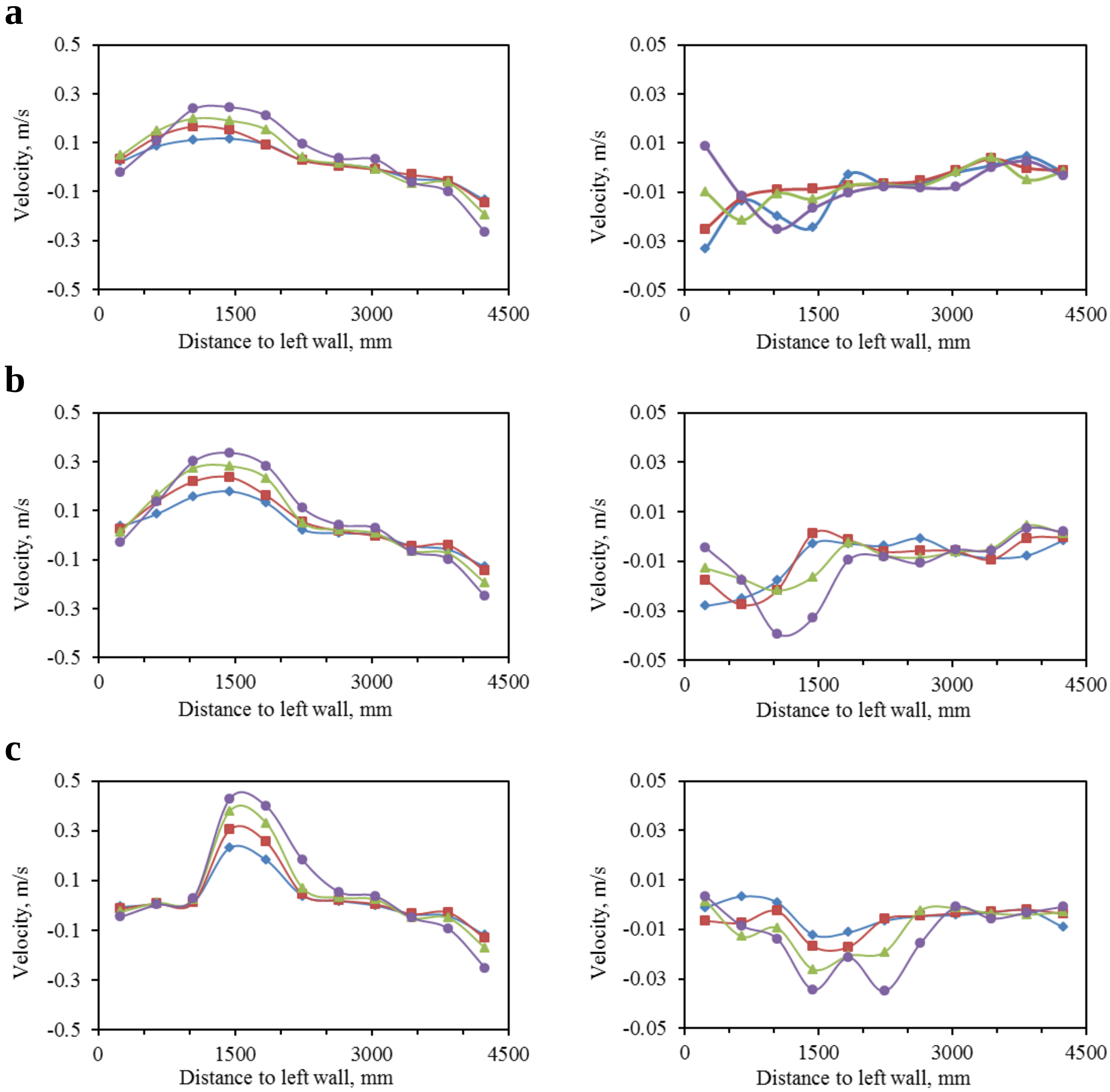

Fig. 2.4 - Measured vertical air velocities near floor along the length of climate chamber with two types of air inlets: Left - wall jet inlet and Right - diffusion ceiling inlet; and with three different floor types: (a) fully slatted floor; (b) 1/3 drain floor + 2/3 slatted floor; (c) 1/3 solid floor + 2/3 slatted floor, where -◆-, -■-, -▲-, and -●- represents 30%, 50%, 70%, and 90% of the designed capacity of ventilation rate (VR_c), respectively.

Generally, increased ventilation rate or $\mathrm{VR_r/VR_c}$ resulted in higher vertical air velocities either downward or upward at the measuring points along the near-floor region in all cases (Fig. 2.4). In system-W, airflow was driven downward near right sidewall and moved upward near left sidewall. For all the three investigated floor types in system-W, the maximum downward velocity was found at the measuring point closest to the right side wall, while the maximum upward velocity happened at measuring points with a distance approximately 1500 mm away from the left side wall, which was 1/3 of the length of chamber. As the presence of two exhaust openings on left sidewall which made a dominant airflow towards right, the vertical air velocities at locations close to the left sidewall were very low in system-W for all three types of floor. For the SS floor, very low vertical velocities occurred in almost the entire solid floor region (Fig. 2.4c). For all the four ventilation rates in system-W, the maximum vertical velocity in DS floor was found higher than that in FS floor but lower than that in SS floor.

In system-C, the vertical air velocities were much lower compared with those in system-W (Fig. 2.4). Airflow at most part of the floor region moved downward in system-C. Higher vertical air velocities were observed at locations near the left sidewall (0 to 1500 mm away from left wall) for FS and DS floor types, and near the middle of chamber (1500 mm to 2500 mm away form left wall) for SS floor.

Fig. 2.5 illustrates the variation of the measured mean air velocities following the change of three influential factors. The mean air velocity increased with increasing ventilation rate for all of the three floor types both in system-W and system-C. It is also shown that much higher mean air velocities occurred in system-W than in system-C. In system-W with all the four ventilation rates, no clear difference was found among the three floor types. In system-C, the mean air velocity increased as the floor opening ratio increased (FS > DS > SS) at 30% and 50% of $\mathrm{VR_r/VR_c}$. When the $\mathrm{VR_r/VR_c}$ was 70% and 90%, highest to lowest mean air velocity was found in DS, FS, and SS floor, respectively.

2.3.2. Turbulence intensity

Fig. 2.6 summarizes turbulence intensities (Ti) near the floor region along the length of climate chamber with two types of air inlets and four floor types under varied ventilation rates. There was no clear difference in Ti following the variation of ventilation rate or $\mathrm{VR_r/VR_c}$. The values of Ti were generally much higher at most part of the floor region in system-C than in system-W for each floor type.

In system-W, a similar tendency for Ti changes along the floor length was occurred among all the four ventilation rates under each floor type. For FS and DS floor in system-W, there were two peaks of Ti, one at the floor region next to the right side wall, another at floor region in the middle of chamber (Fig. 2.6ab). For the SS floor in system-W, one more peak occurred at region 1000 mm away from left sidewall beyond the two peaks similar as FS and DS floor (Fig. 2.6c).

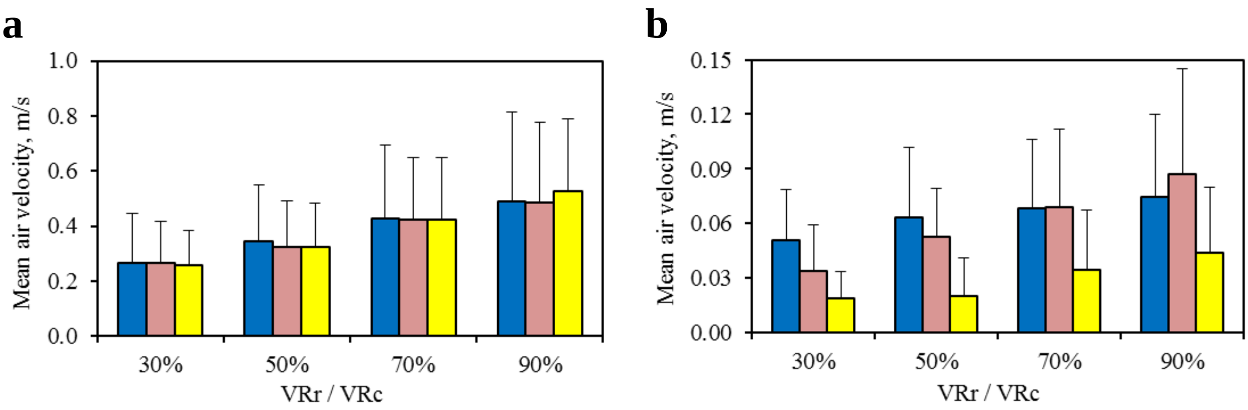

Fig. 2.5 - Mean air velocity at near floor region versus ventilation airflow rate with different floor types and different air inlets, where ▆, ▆, and ▆ represents (1) fully slatted floor, (2) 1/3 drain floor + 2/3 slatted floor, and (3) 1/3 solid floor + 2/3 slatted floor, respectively. In the figure, (a) is from wall jet air inlet and (b) is from diffusion ceiling air inlet. VR_r/VR_c is the ratio of room ventilation rate to the designed capacity of ventilation rate, which 800 m^3 h^{-1} in this study.

In system-C, there was no clear tendency for Ti changes along the floor length among four ventilation rates (Fig. 2.6). Lower Ti was found for in FS floor than for DS and SS floor (Fig. 2.6bc). Two peaks of Ti were found next to both side walls for FS floor (Fig 2.6a).

The variation of the mean Ti was shown in Fig. 2.7. There was no significant difference in Ti above the floor among the four levels of ventilation rate. Much higher mean Ti was found in system-C than in system-W. In system-W, the mean Ti increased as the floor opening ratio increased (FS > DS > SS) for all the four ventilation rates, while in system-C the mean Ti increased as the floor opening ratio decreased (FS < DS < SS) at 30% to 70% of VR_r/VR_c.

2.3.3. Airflow pattern

Fig. 2.8 shows the airflow patterns inside the chamber from smoke visualization tests at the ventilation level of 90% VR_r/VR_c. In system-W, the inlet air injected from wall-jet opening reached the ceiling first and continued to the far end wall. On reaching the floor it roughly split into two: a primary return airflow above the floor and another penetrating flow into the pit space through floor openings. The three different floor types in system-W resulted in some difference of airflow pattern near the exhaust opening zone. For FS and DS floor, air near the left wall in the pit had an upward trend, but no such trend was found for SS floor. In system-C, no clear big flow pattern was observed. The supply air from diffusion ceiling inlet dropped down slowly and flow to the left. There were many small turbulence vortices in the chamber. No much difference among the three floor types in system-C.

2.3.4. Air exchange rate

The air exchange rate (ACH) between room and pit spaces was calculated using vertical velocity along the near-floor region and the area of floor openings. Fig. 2.9 shows the ACH variation under different treatments. For a same ventilation rate and floor type, more ACH was found in system-W than in system-C. In system-W, higher ventilation rate and greater floor opening ratio resulted in higher ACH. However in system-C, the ventilation rate had limited influence on the ACH changes. In system-C, more air exchanged between room and pit spaces following greater floor opening ratio at lower ventilation rate (30% and 50% of VR_r/VR_c).

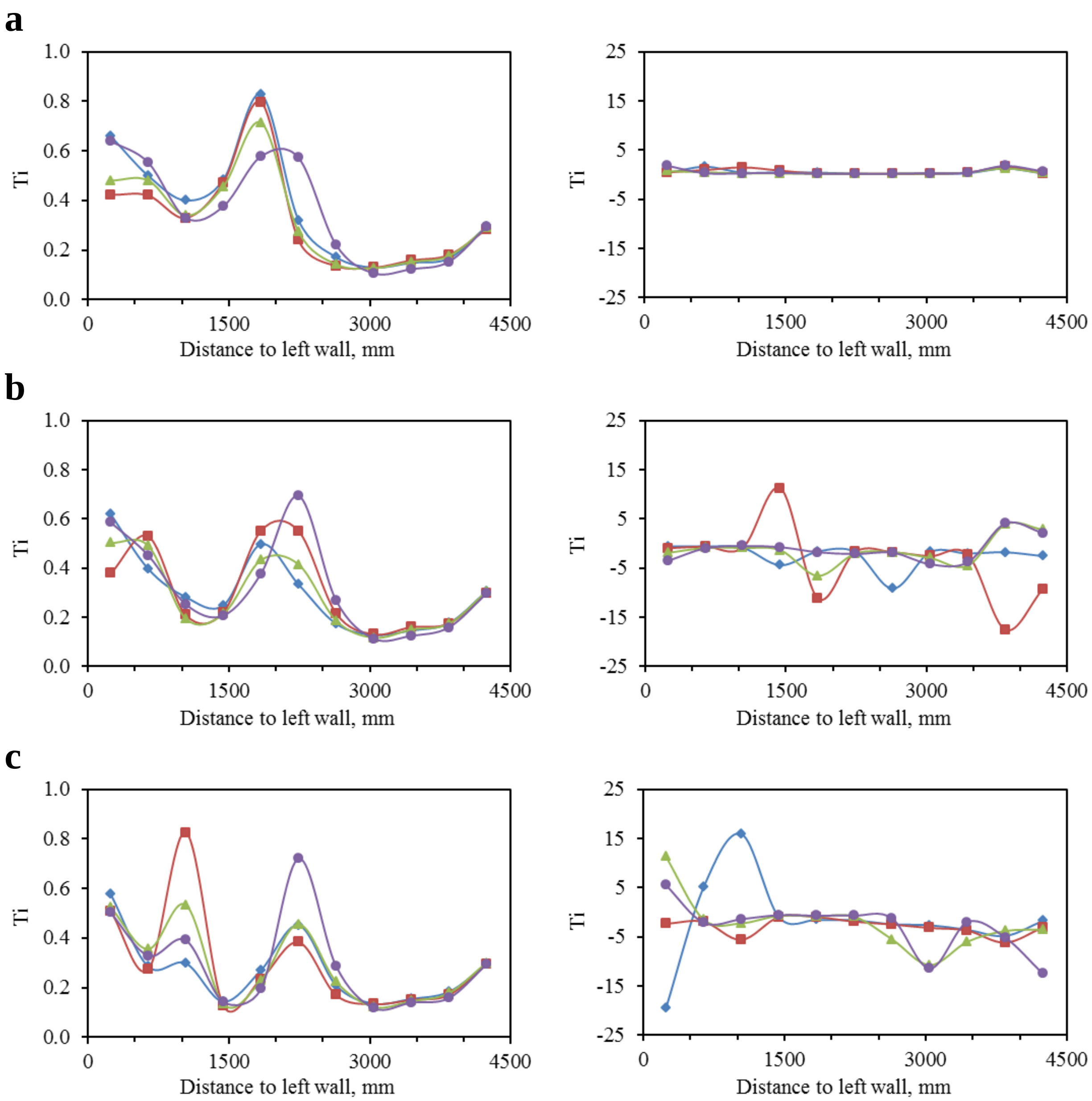

Fig. 2.6 - Measured turbulence intensities near floor along the length of climate chamber with two types of air inlets: Left - wall jet inlet and Right - diffusion ceiling inlet; and with three different floor types: (a) fully slatted floor; (b) 1/3 drain floor + 2/3 slatted floor; (c) 1/3 solid floor + 2/3 slatted floor, where -◆-, -■-, -▲-, and -●- represents 30%, 50%, 70%, and 90% of the designed capacity of ventilation rate (VR_c), respectively.

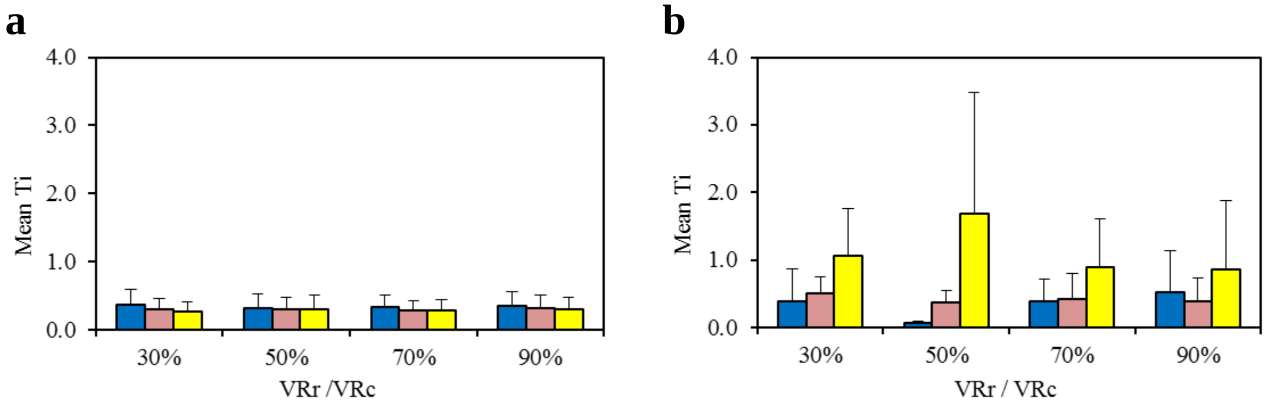

Fig. 2.7 - Mean Ti versus ventilation airflow rate with different floor types and different air inlets, where , , and represents (1) fully slatted floor, (2) 1/3 drain floor + 2/3 slatted floor, and (3) 1/3 solid floor + 2/3 slatted floor, respectively. In the figure, (a) is from wall jet air inlet and (b) is from diffusion ceiling air inlet. VR_r/VR_c is the ratio of room ventilation rate to the designed capacity of ventilation rate, which 800 m^3 h^{-1} in this study.

2.4. Discussion

2.4.1. Effect of ventilation rates

Higher ventilation rate resulted in higher near-floor air velocity, which was in accordance with previous study. Strom et al. (2002) found a linear correlation between supply air velocity and the air velocity near floor region in a slot-ventilated building. Ye, Zhang, et al. (2009) observed inlet air velocity increased with increasing ventilation rate, and resulted in a higher air velocity at the manure surface in a scale model of pig house. In this study, the inlet air velocity increased with increasing ventilation rate (Table 2.3), and this caused a higher velocity when air dropped down to the floor region (Fig. 2.4 and Fig. 2.5). A higher air velocity near the floor region also enhanced the air exchange rate between pit and room spaces in system-C (Fig. 2.9).

2.4.2. Effect of air inlets

Although a same amount of air was supplied for both systems, the inlet air velocity was found much lower in system-C than in system-W (Table 2.3). The inlet opening of system-W was a small window opening which was less than 0.07 m^2, while for system-C it was the whole area of ceiling, which was 5.21 m^2. The large area difference of inlet openings resulted in the difference of inlet air velocity between the two systems. Besides, in system-C, outdoor air needed to go through the insulated diffusion ceiling to enter into the chamber. The diffusion ceiling created large resistance force as air passing through it. However, in system-W, outdoor air was directly injected into the chamber via the wall jet inlet opening. As mentioned above, the near-floor air velocity has a linear correlation with the inlet air velocity (Strom et al., 2002). Higher inlet air thus resulted in higher near-floor air velocity was found in system-W than in system-C (Fig. 2.5). The higher near-floor air velocity also made the ACH between room and pit spaces higher in system-W than in system-C (Fig. 2.9).

A big return flow was observed in system-W but no clear airflow pattern in system-C. The return flow from the wall jet inlet was in accordance with jet flow decay theory. Since the inlet air velocity was too low, no clear airflow pattern was found in system-C. Due to the missing of significant turbulent vortex in system-C, small turbulent vortices made near-floor Ti higher with lower velocity in system-C than in system-W (Fig. 2.7).

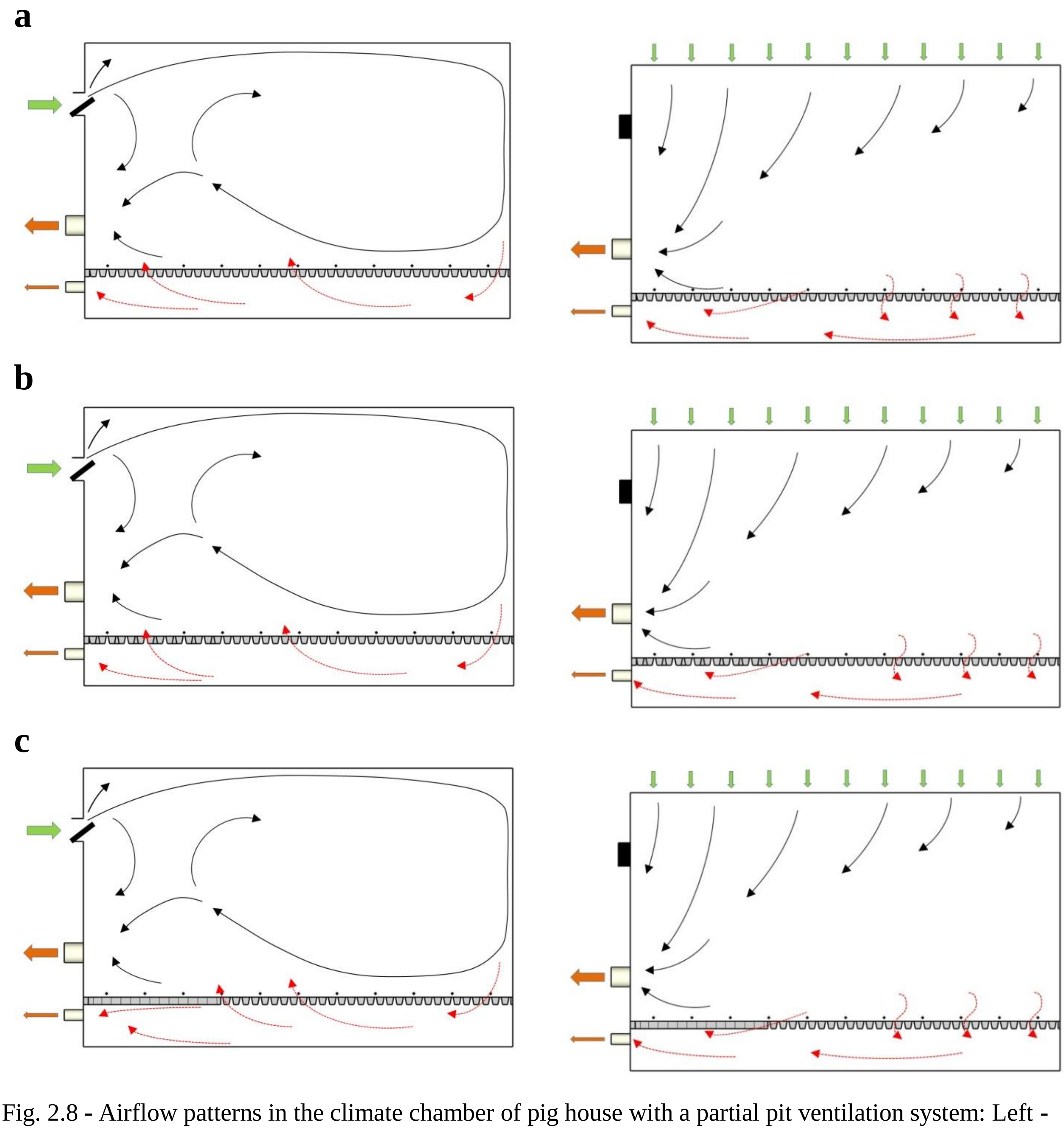

Fig. 2.8 - Airflow patterns in the climate chamber of pig house with a partial pit ventilation system: Left - wall jet inlet and Right - diffusion ceiling inlet; (a) fully slatted floor; (b) 1/3 drain floor + 2/3 slatted floor; (c) 1/3 solid floor + 2/3 slatted floor.

In the real condition, a large amount of heat produced by animals can create heat buoyancy flow which will make a more clear airflow pattern inside the room with diffusion ceiling air inlet. Further investigations on heat buoyant flow for system-C are needed in the future.

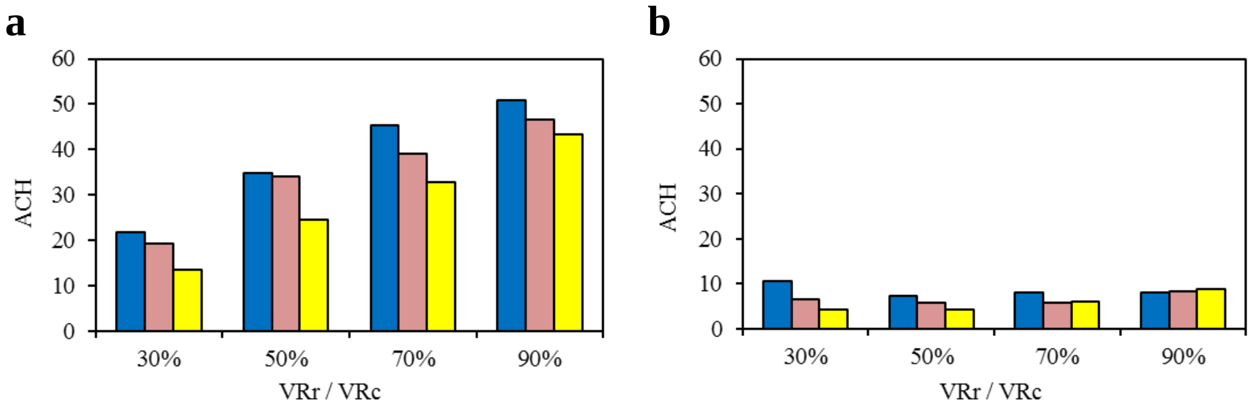

Fig. 2.9 - Air exchange rates between room and pit spaces varied following different ventilation rate, where (blue), (orange), and (yellow) represents (1) fully slatted floor, (2) 1/3 drain floor + 2/3 slatted floor, and (3) 1/3 solid floor + 2/3 slatted floor, respectively. In the figure, (a) is from wall jet air inlet and (b) is from diffusion ceiling air inlet. VR_r/VR_c is the ratio of room ventilation rate to the designed capacity of ventilation rate, which is 800 m3 h-1 in this study. ACH represents air exchange rate, $m^3 s^{-1}$.

2.4.3. Effect of floor types

The three types of floor with different opening ratios (Table 2.1) had different influences on airflow characteristics. As the air can either enter into or exit the pit headspace via floor openings, the floor slots function as both air inlets and outlets for the pit headspace. Higher vertical air velocity near the floor region and higher floor opening ratio resulted in higher ACH of slurry pit.

For system-W, the results were in agreement with previous studies investigating the effects of slatted floors on ACH between room and pit spaces (Ye, Zhang, Li, Strøm & Dahl, 2008; Ye, Zhang, et al., 2009; Zhang et al., 2008). Increasing the opening ratio of floor enhanced the ACH between the room and slurry pit.

In system-W with a big dominant turbulent vortex and higher air velocity, Ti increased as floor opening ratio increased. Air became more turbulent as passing through larger slots. In system-C with many small turbulent vortices, air became more turbulent as passing through smaller slots.

2.4.4. Ammonia emissions

The dispersion of ammonia emission from slurry pit under slatted floor is related to airflow patterns, air velocities, turbulence levels and air exchange rate in the pit headspace (J. Ni, 1999; Ye, Zhang, et al., 2009; Zhang et al., 2008).

Higher ventilation rate and higher air velocity near the emission surface will enhance the emission rate (Ye, Zhang, Li, Strøm & Dahl, 2008; Zhang et al., 2008). Increasing the opening ratio of slatted floor increased the air exchange rate in the slurry pit, resulting in a higher ammonia emission rate

(Ye, Zhang, Li, Strøm & Dahl, 2008). Elzing and Monteny (1997) considered the influence of Ti on ammonia emission was more effective at low air velocities than at high air velocities. Ye, Zhang, Li, Strøm, Tong, et al. (2008) found Ti had significant influence on NH_3 emission when air velocities below 0.25 m s^{-1} and NH_3 emissions reduced following Ti decrease.

Under same ventilation rate, system-C with diffusion ceiling inlet resulted in lower air velocity near the emission surface and lower air exchange rate in the pit compared with system-W with wall-jet air inlet. Lower ammonia emission rate was also expected in system-C than in system-W. This is agree with a field experiment conducted by Zong, Feng, et al. (2014) that more ammonia emission from the fattening pig room with wall jet air inlet. However, more work is required to investigate the effect of system-C on ammonia emission as turbulence plays important role.

2.5. Conclusion

In an experimental chamber equipped with partial pit ventilation system, air velocities, turbulence intensities and airflow patterns near the floor region and air exchange rate between room and pit spaces were affected by different ventilation rates, air inlet types and floor types. Higher ventilation rate resulted in higher near-floor air velocity and higher air exchange rate in the pit. Much higher air velocities and lower turbulence intensities were observed in ventilation system with wall jet inlet (system-W) than in the one with diffusion ceiling inlet (system-C). A big dominant return flow was found in system-W, while small turbulent flows were found in system-C. Increasing the floor opening ratio enhanced the air exchange rate in the pit. Results for ammonia emission from a field study regarding PPV combined with different air inlets can be comprehensively explained by using the results of this study.

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Chapter 3

Effects of different air inlets on indoor air quality and ammonia emission from two experimental fattening pig rooms with partial pit ventilation system – Summer condition

Paper II:

Zong, C., Feng, Y., Zhang, G., Hansen, M.J., 2014. **Effects of different air inlets on indoor air quality and ammonia emission from two experimental fattening pig rooms with partial pit ventilation system – Summer condition.** *Biosystems Engineering*, Vol. 122, P 163-173.

Abstract

It has previous been demonstrated that a pit ventilation system could improve indoor air quality and reduce ammonia emission significantly from pig production if an air purification system was installed to treat the pit exhaust air. However, the knowledge about the influence of a partial pit exhaust unit treating a small part of the ventilation (10%) in a ventilation system with different types of air inlets on indoor air quality and ammonia emission from pig house is still lacking. In this study, two rooms, both with partial pit exhaust and ceiling-top room exhaust units, were used. One room was equipped with ceiling air inlet (system C) and another room was equipped with wall jet air inlet (system W). Each room had 32 fattening pigs. The maximum ventilation rate in each room was set as 3200 $m^3 h^{-1}$. Room ventilation rate was automatically controlled by a climate control strategy based on indoor thermal conditions, while pit ventilation rate was fixed at 10% of the maximum ventilation rate. Ammonia concentrations were measured in air inlet, room exhaust and pit exhaust for both systems. Air flow rates and ammonia concentrations were measured and recorded continuously. Results showed that ventilation rate requirement was higher in system C than in system W (22.3%, $p < 0.001$) to maintain the setup indoor thermal condition during the whole fattening period. In the meantime, significant higher ammonia concentrations and emissions in both pit and room exhausts were found in system W than in system C ($p < 0.001$). The ammonia emission ratio of pit exhaust, defined as the emission via pit exhaust divided by the total emission, in systems C and W was 48% and 47%, respectively. If applying an effective air purification system, a significant reduction of ammonia emission could be achieved. The gap of ammonia concentration difference between system C and W increased in the later stage. Higher room ventilation rate led to smaller difference of ammonia concentration in room air. Slurry depth had a positive effect on the ammonia emission from pit exhaust. No significant difference in the pigs' activity was found between the two ventilation systems.

Keywords: *partial pit air exhaust, ventilation design and control, emission reduction, indoor air quality, air purification unit*

3.1. Introduction

Ammonia concentration is one of the most concerned variables for determining air quality in pig house as it has a significant impact on the health of both human beings and animals inside the building (Saha, Zhang, Kai & Bjerg, 2010; Ye, Zhang, Li, Strøm & Dahl, 2008; Zhang et al., 2005). Meanwhile, ammonia emission from livestock buildings is always a nuisance to the neighbouring atmospheric environment (Hutchings, Sommer, Andersen & Asman, 2001; Sommer et al., 2006). Intensive investigations regarding this agricultural aerial pollutant have been carried out.

Mechanical ventilation is considered to be a basic control method to eliminate ammonia pollution from livestock production (Cho, Ko, Kim & Kim, 2012) when air purification systems is added at the ventilation exhaust (Zucker, Scharf, Kersten & Müller, 2005). Designs of mechanical ventilation system, including configuration and locations of air inlets and outlets etc., and ventilation control strategy can significantly influence the airflow characteristics inside a room, which can further influence the dispersion and deposition of ammonia and other gaseous contaminants (Arogo, Westerman & Heber, 2003; Buiter & Hoff, 1998; Ye et al., 2008; Zhang & Strom, 1999). Mechanical ventilation system with only roof or ceiling mounted exhaust units has been applied in Danish pig production for many years. However, this conventional ventilation system has disadvantage of ineffective control of indoor environment, especially when an air purification system is required to abate ammonia emissions (Pohl & Hellickson, 1978; Saha et al., 2010). In order to improve the control efficiency, a pit exhaust ventilation system locating the outlet near the main source zone of pollutants has developed (Vantklooster, Roelofs & Gijsen, 1993). High concentrated air pollutants from the pit headspace can be extracted directly *via* pit exhaust to the air purification systems.

Investigations on pit exhaust ventilation systems in pig houses have been reported in the literature. Pohl and Hellickson (1978) investigated performances of five full pit ventilation systems in a 1/12 size scale model swine finishing building to study air distributions and found that centred duct pit ventilation system was the best. Effects of building design and management factors on ammonia distributions in a one half scale model with a full pit ventilation system were studied by Buiter and Hoff (1998). These studies demonstrated that full pit ventilation systems could improve the indoor air quality, but also result in increased total emission. The partial pit ventilation system reported by Saha et al. (2010) consisted of a ceiling diffusion air inlet, a ceiling-top ventilator as a major room exhaust unit and a pit exhaust unit. Saha et al. (2010) showed that the ammonia concentration in room air using the partial pit ventilation (around 3.8 ppm) was reduced by 42.6% compared with a system with only ceiling-top exhaust (around 6.6 ppm). Moreover, ammonia emission could be significantly reduced by using the partial pit ventilation system in combination with an air purification system. The capacity required for air cleaning in the partial pit ventilation system was only 10% of the maximum total room exhaust air. The partial pit ventilation could improve both the indoor air quality and the reduction of ammonia emission if a validated air purification processing was used. However, up to date, the information of a partial pit ventilation system combined with different air inlets has not been reported in literature yet.

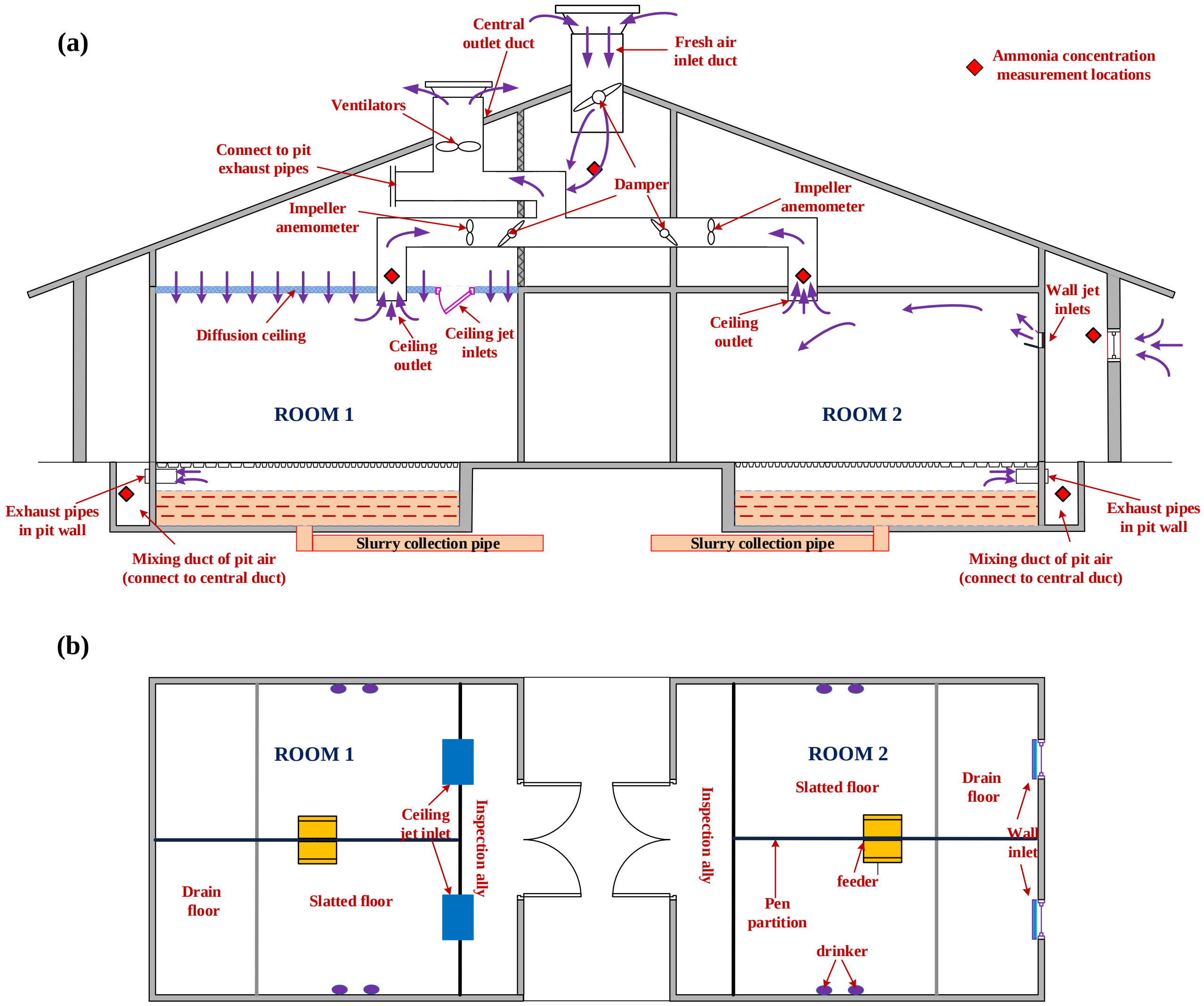

Fig. 3.1 - (a) cross-section of the experimental building; (b) floor plan of the investigated rooms.

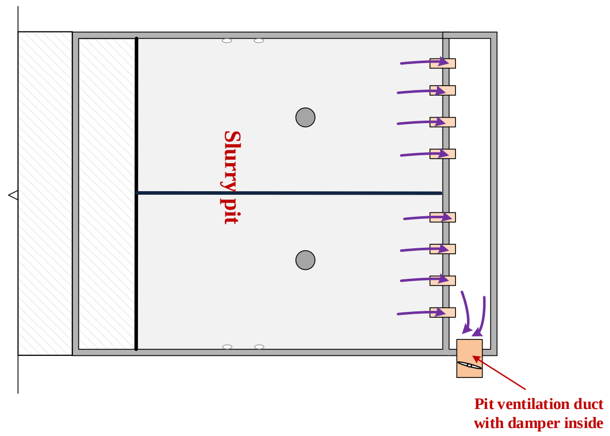

Fig. 3.2 - Pit ventilation system underneath the floor in one room (both rooms have the same layout).

Thus, the objectives of the present study was to investigate the effects of two different air inlets, a wall jet air inlet and a ceiling diffusion/jet air inlet, on indoor air quality and ammonia emission from fattening pig rooms with partial pit ventilation systems; and generate knowledge on application of partial pit ventilation system.

3.2. Materials and methods

3.2.1. Pig house

The experimental pig production house (Fig. 3.1) at the Research Centre Foulum, Aarhus University, Denmark, was used for this investigation. The dimensions and layout of the experimental rooms were designed according to a commercial Danish pig production unit. The room height was 2.67 m. Each room had two pens (4.8 m long and 2.45 m wide) that were equally divided by a 1 m high partition wall (Fig. 3.1a). There was an inspection alley with a width of 0.9 m on the door side (Fig. 3.1b). All pens were equipped with two thirds slatted floor and one third drain floor (Fig. 3.1b). The drain floor was a type of slatted floor with smaller slot opening. The opening ratio of the slatted floor and drain floor was 17.2% and 8.6%, respectively. Each pen had its own 0.7-m deep slurry pit underneath the floor. Slurry could be pumped out of the pit to an outdoor slurry tank through valves in the bottoms of the pit (Fig. 3.1a). One feeder and two drinkers were installed in each pen (Fig. 3.1b). The drinking troughs were attached on the side walls, while the feeders were on the partition walls between the pens. The two rooms were connected by a 2.3-m wide corridor in the middle (Fig. 3.1a). This pig house was designed to facilitate laboratory tests of various ventilation systems and operation strategies.

3.2.2. Ventilation systems

The experimental building was equipped with a negative pressure ventilation system, which was commonly applied in Denmark. The two rooms had the same layout of exhaust units: each with a partial pit exhaust and a ceiling-top room exhaust. A central outlet duct was installed near the building ridge (Fig. 3.1a) where a negative pressure was created by two ventilators (REVENTA® GmbH & Co. KG, Germany). All exhaust units in the facility were connected to this central outlet duct. The airflow rate in each exhaust was regulated by an analogue controlled damper (VengSystem A/S, Denmark) inside the exhaust duct (Fig. 3.1a).

The room exhaust unit consisted of a 0.46-m diameter chimney duct and an impeller anemometer in the chimney duct. The chimney duct was the major air outlet (Fig. 3.1a). The anemometer was accompanied with a frequency converter (VengSystem A/S, Denmark) to measure airflow rate that was created by the central outlet duct and regulated damper. The capacity of the room exhaust unit was pre-adjusted to approximately 3200 $m^3 h^{-1}$. Room ventilation rate was automatically controlled by the VengSystem based on indoor thermal conditions during the experiment.

The pit exhaust openings were located under the drain floor (Fig. 3.2). Each pen had four pit exhausts made of *polyvinyl chloride* (PVC) pipes of 0.16 m in diameter installed in the side wall of the pit. The exhaust air from pit headspace was extracted through these pipes into a ventilation duct located at the side of the building (Fig. 3.2). Same as the room ventilation duct, pit ventilation duct was also equipped an impeller anemometer and a frequency converter (VengSystem A/S, Denmark) to measure airflow rate. The analogue controlled damper (VengSystem A/S, Denmark) in pit ventilation duct was kept fixed during the experiment. The pit ventilation rate was set approximately 10% of the maximum total ventilation rate for both rooms during the experiment.

The only difference between the two rooms was the air inlets. Room 1 was equipped with ceiling diffusion/jet air inlet (system C) and room 2 had wall jet air inlet (system W).

3.2.2.1. System C

System C with diffusion ceiling and ceiling jet air inlets plus partial pit ventilation system was operated in Room 1 (Fig. 3.1). Three air inlet ducts of 0.8 m in diameter located in the building ridge allowed fresh air to enter the building attic (Fig. 3.1a). Each air inlet duct had a damper plate to regulate the opening ratio. The attic above room 1 was connected to the attic air entry space under those ducts. The ceiling was made of porous materials consisted of compressed straw plate and mineral wool isolation layer. It could diffuse supplied air from the attic into the room under negative pressure. Two ceiling-jet air inlets were installed in the ceiling near the inspection ally. Those ceiling-jets were normally closed. However, they would open gradually to increase the air speed in animal occupied zones (AOZ) when the room temperature increased above the set temperature of 20.4 ℃ for the experiment. A P-band of 2.4 ℃ was used to prevent the ceiling jets from being open and closed too frequently.

3.2.2.2. System W

System W with wall jet air inlets plus partial pit ventilation system was operated in Room 2 (Fig. 3.1). Two wall-jet air inlets (0.62×0.24 m) with bottom hinged flap and adjustable top guiding plate were installed in the sidewall opposite the inspection alley in room 2 (Fig. 3.1b). Both wall jets were placed 1.83m above the floor, and in the symmetrical plan of each pig pen. The inlet openings were regulated automatically together with room exhaust ventilation rates. The set temperature was 20.4 ℃ with a P-band of 3.3 ℃. The guiding plate was designed to guide the inlet air direction, which had an angle of 40 degrees to horizontal position during this experiment.

3.2.3. Animals and feeding

The experiment was carried out from 6th August to 23rd October, 2012. A total of 64 pigs were randomly picked and equally divided into the two rooms. Those pigs were weighed three times during experiment. The average pig weights were about 30 ± 3.1 kg in the beginning and 111.8 ± 10.3 kg at the end of the experiment. Feed and water were supplied *ad libitum*. A standard diet with two types of feed for growing-finishing pigs (feed content can be found in Appendix) was provided to those pigs. One feed was used in earlier stage, and another one changed at day 32 in the later stage. Straw was supplied on the drain floor area as rooting materials based on Danish regulations. The mean pigs' growth rate was 1.05 ± 0.13 kg d^{-1} in system C and 1.08 ± 0.11 kg d^{-1} in system W. There was no significant difference in pigs' weights ($P > 0.05$) between system C and system W.

3.2.4. Measurements

3.2.4.1. Ventilation rates and air flow patterns

Ventilation rates through the room and pit exhaust units were measured and recorded automatically by the VengSystem (VengSystem A/S, Denmark). The flow rates in all exhausts were measured every minute based on the pulse signals generated by anemometer rotating, which was linear with air flow rate. The flow rate measurement devices (REVENTA® GmbH & Co. KG, Germany) were pre-calibrated using a facility built of a wind tunnel and ISO-standard nuzzles, and the coefficient of determination (R^2) could reach up to 0.9981.

Smoke tests were conducted before the pigs were placed into the rooms to observe the air flow patterns under different ventilation systems. A portable smoke generator (Z-series II, Antari Ltd., Taiwan) was used to generate smoke in front of the air inlet units. In system W, air with smoke particles was injected through wall jet air inlets. In system C, air with smoke particles was injected through diffusion ceiling and ceiling jet air inlets.

3.2.4.2. Ammonia concentration

Air samples collected from (i) the attic just beneath the roof inlet ducts (system C background), (ii) the room exhaust unit in room 1, (iii) the slurry pit exhaust pipe of room 1, (iv) the outside of the wall inlet of room 2 (system W background), (v) the room exhaust unit in room 2, (vi) the slurry pit exhaust pipe of room 2 (Fig. 3.1a), were measured using an INNOVA infrared 1412 Photoacoustic Field Multi-Gas Monitor and a 1309 Multipoint Sampler (LumaSense Technologies Inc., USA). Six pumps (Model-CAPEX L2, Charles Austen Pumps Ltd., UK) were connected to insulated Teflon tubes (outer diameter 8 mm and inner diameter 6 mm) and were used to suck air samples from the above mentioned locations to the multi-gas analyser. The insulation of the Teflon tubes was employed to avoid the risk of water condensation during measurement. The monitor had optical filter UA0973 with a detection limit of 0.2 ppm ammonia. The calibration of ammonia measurement using INNOVA 1412 photoacoustic field gas-monitor was conducted by LumaSense Technologies Inc. During the calibration, the ambient temperature and pressure was kept at 24.4 ℃ and 1011 mbar, respectively, with nitrogen as zero air. Calibration results showed a standard deviation of 0.118 ppm at 31.3 ppm ammonia concentration. The air sampling period for each measurement was 40 s, followed by 20 s flushing time to replace the exhausted air in the measuring chamber of the Monitor before a new measurement started. To reduce the interference between locations, the measuring sequence was from locations with high concentration to locations with low concentration. As a result, air samples were measured with an order of (iii), (vi), (ii), (v), (i) and (iv). Ten 1-minute measurements were made continuously for each sampling location; but only the last minute data was used for ammonia concentration at the location.

3.2.4.3. Air temperature and relative humidity

Temperature and relative humidity inside both rooms and outside the pig building were measured by VE10 and VE14 Sensors (VengSystem A/S, Denmark) and recorded using VengSystem software. Besides, type T thermocouples connected to a data logger (Eltek Ltd, England) were also used to measure air temperatures (i) in the attic (air inlet of room 1), (ii) outside the wall jet inlets of room 2, (iii) inside both rooms, one 2 m above the fully slatted floor and the other 2 m above the drain floor of each pen, (iv) in the headspace of slurry pits. Relative humidity was regularly checked using a Veloci Calc multifunction velocity anemometer (Model 9565, TSI Inc., USA).

3.2.4.4. Slurry depth

Slurry depth was measured twice a week at a fixed location near the inspection alley in each slurry pit. To avoid slurry blocking the pit air exhausts, slurry tank would be emptied through the valves in the bottom of the pits when the measured depth of stored slurry was close to or more than 30 cm.

3.2.4.5. Pig behaviour

The behaviours of the pigs in each pen were monitored by four video cameras (Storage Options, China). Videos were recorded by a Video Server (Storage Options, China) with 1 h interval and transferred to the computer via an internet cable. The recorded videos were used to distinguish the number of lying pigs and standing pigs. Active pig time was defined as the time when a pig was not lying (Aarnink & Wagemans, 1997).

3.2.5. Observations

Day 20, 46, and 77 were chosen as observation days of pig behaviours to represent beginning, middle and end of the period. The behaviour of animals was an important indicator for animal's wellbeing and could also affect the indoor climate and air quality. The activities like eating, drinking or lying of the pigs would affect not only the air distribution in the AOZ, but also air exchange rates between rooms and pit headspace. When a pig lay on the floor, it would occupy more space than the one standing there. The movements of animals could create turbulent vortices.

3.2.6. Computational of ammonia emission rate and data analysis

Ammonia emission rate can be calculated by the following equation:

$$E_{NH_3} = V(C_{out} - C_{in})$$

where E_{NH_3} is the ammonia emission rate either from the room exhaust unit or from the pit exhaust unit, mg h^{-1} pig^{-1} or mg d^{-1} pig^{-1}; V is the ventilation rate, either for room or pit, m^3 h^{-1} pig^{-1} or m^3 d^{-1} pig^{-1}; C_{out} is the outlet ammonia concentration of either room air or pit exhaust air, mg m^{-3}; C_{in} is the inlet ammonia concentration from attic for system *C* and from side wall inlet for system W, mg m^{-3}.

The t-test analysis was used to evaluate the effects of different air inlets on ammonia concentrations and emissions.

3.3. Results and discussion

3.3.1. Climate characteristics

3.3.1.1. Temperature and relative humidity

A significant difference between mean room temperatures in the two systems ($p < 0.001$) was found (Table 3.1). Room temperatures had a lower fluctuation compared with outside temperature, which changed dramatically between day and night. There was no significant difference in the daily mean temperatures measured in the headspace of the slurry pit between the two systems ($p > 0.05$). The relative humidity inside both rooms was similar with each other.

3.3.1.2. Ventilation rates

When outdoor temperature was higher, the ventilation rate requirement was higher as well (Fig. 3.3). Since this investigation was conducted from August to October, the daily mean outdoor temperatures decreased as the experiment proceeded. There were two periods between days 45 to 51 and days 60 to 73 with relatively low outdoor temperature, during which the ventilation rates were also the lowest. The diurnal pattern of the mean room ventilation rates in both systems is given in Fig. 3.4, which followed a similar pattern of the outside temperature as well.

The average room ventilation rate was 22.3% higher in system W (83.36 $\pm$16.32 $m^3\ h^{-1}\ pig^{-1}$) than in system C (68.14 $\pm$19.49 $m^3\ h^{-1}\ pig^{-1}$). It was noticed that the room ventilation rate in system W changed more rapidly and dramatically than that in system C. This was because when the outdoor air came into system C, it needed to go through the attic first and then pass through the insulated diffusion ceiling. Consequently, the temperature of the supply air was warmed up in the attic space and through the insulated ceiling materials. However, for system W, outdoor air came into the room directly through the windows. As a result, the inlet air was cooler in system W than in system C. Higher fluctuation was also identified in the air supply for system W. To maintain a same comfortable indoor temperature, more fresh air was required for system C than for system W. As this study was conducted during warm seasons, a large amount of fresh air was supplied into the pig rooms mainly to keep a desired indoor thermal condition. During cold seasons, the fundamental purpose in the control criteria to is keep acceptable moisture and aerial contaminant levels inside the pig building. A minimum ventilation rate for exchanging fresh air with room exhaust air would be implemented. Therefore, there will be no such big difference on ventilation requirement between the both systems. However, a cold stress issue should be considered in system W in winter to ensure sufficient mixing of the cold fresh air with the warm room air before the fresh air reached the animal occupied zone (AOZ) (Zhang, Morsing & Strom, 1996; Zhang & Strom, 1999).

Pit ventilation rates in the two systems were close with each other (Table 3.1& Fig. 3.3) with diurnal fluctuations (Fig. 3.4). During night, the damper in the room ventilation duct allowed less air getting out of the rooms than during the day, but the damper in pit ventilation duct was fixed. As the pressure in the central outlet duct was almost kept constant, more air escaped out *via* pit exhausts in the evening. The mean diurnal pattern (Fig. 3.4) shows that the pit ventilation rates were maintained between 9.0 to 10.3 $m^3 h^{-1} pig^{-1}$.

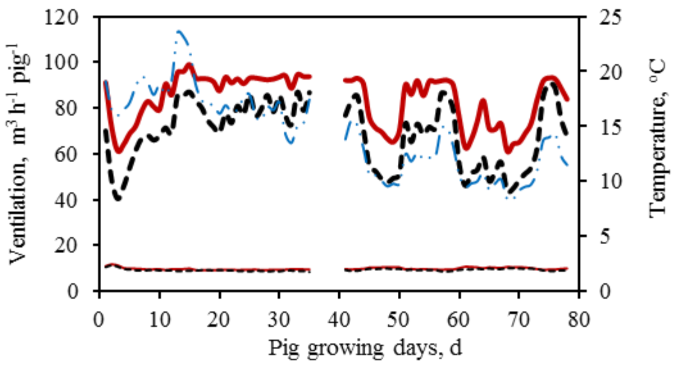

Fig. 3.3 - Daily mean temperatures and ventilation rates during the pigs' growing period: ▬▬, room ventilation rate in system C; ▪▪▪▪▪, room ventilation rate in system W; ——, pit ventilation rate in system C; -----, pit ventilation rate in system W; − · · −, outside temperature.

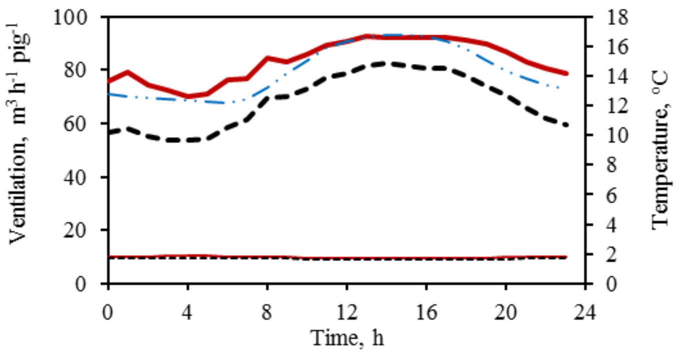

Fig. 3.4 - Mean ventilation rates and outside temperature at the same hours of the measuring days: ▬▬, room ventilation rate in system C; ▪▪▪▪▪, room ventilation rate in system W; ——, pit ventilation rate in system C; -----, pit ventilation rate in system W; − · · −, outside temperature.

3.3.1.3. Airflow patterns

Smoke tests revealed that air in system W reached the ceiling first. Fresh air travelled around two third of the pen length and started to drop, and then had a return near the animal occupied zone. This observed air flow pattern agreed with the free jet drop model developed by Zhang *et al.* (1996). In system C, supplied air dropped down slowly and smoothly through diffusion ceiling. When ceiling jets were open, fresh air was injected into the drain floor area with high speed and almost no air through diffusion ceiling.

Short circuiting of the incoming air from wall inlets to the room exhaust opening could hardly be observed in system W. In system C, short circuiting of incoming air through the diffusion ceiling occurred in a small portion of ceiling area near the room exhaust opening. The short circuiting of incoming air could dilute the ammonia concentration in room exhaust, and made the concentration value lower in room exhaust air than in AOZ. It had no influence on ammonia emission from the pig room since emission subjected to the mass conservation.

Table 3.1 - Means ± standard deviations of temperature and relative humidity in room and pit air, and ventilation rate through room and pit exhausts

Ventilation System	Temperature (°C)		Relative Humidity (%)		Room ventilation Rate per Pig ($m^3 h^{-1} pig^{-1}$)	Pit Ventilation Rate per Pig ($m^3 h^{-1} pig^{-1}$)
	Room [c]	Pit Headspace	Room [d]	Pit Headspace		
System C [a]	19.2 ± 2.0	20.1 ± 1.7	58.0 ± 6.6	69.8 ± 6.5	83.36 ± 16.32	9.85 ± 0.71
System W [b]	18.4 ± 2.0	20.1 ± 1.5	56.9 ± 5.6	73.9 ± 5.8	68.14 ± 19.49	9.31 ± 0.61
Outside	14.3 ± 4.1		76.0 ± 11.9		-	-

[a] System C – room with diffusion ceiling / ceiling jet inlet.
[b] System W – room with wall jet inlet.
[c] 2 m above the floor.
[d] 1.5 m above the floor.

Table 3.2 - Means ± standard deviations of ammonia concentrations at different locations and ammonia emissions through room and pit exhausts

Measurement	Measurement locations	Ventilation System		Effect of ventilation systems [d]
		System C [b]	System W [c]	
Ammonia concentration, ppm	Room exhaust	2.10 ± 0.69	3.44 ± 1.36	$p < 0.001$
	Pit exhaust	16.62 ± 6.73	21.27 ± 9.06	$p < 0.001$
	Outside [a]	0.58 ± 0.15	0.45 ± 0.13	$p < 0.001$
Ammonia emission, $mg\ h^{-1} pig^{-1}$	Room exhaust	120.7 ± 40.81	158.88 ± 62.33	$p < 0.001$
	Pit exhaust	111.45 ± 48.13	140.2 ± 61.50	$p < 0.001$
	Total	232.15	299.08	-

[a] for system C was in the attic and for system W was outside the wall jet inlet.
[b] System C – room with diffusion ceiling / ceiling jet inlet.
[c] System W – room with wall jet inlet.
[d] Main effect calculated with the t-test statistical model.

3.3.2. Ammonia concentration

Ammonia concentrations at room and pit exhausts were much higher in system W than in system C (Table 3.2). The mean ammonia concentration was 63.8% higher in system W than in system C ($p < 0.001$). For pit exhaust air, it was 28% higher in system W than in system C ($p < 0.001$). Higher fluctuations of ammonia concentration were observed in system W.

Ammonia concentrations in room air in both investigated partial pit ventilation systems were close with the previous study (Saha et al., 2010) and were much lower than in a conventional pig room without a partial pit ventilation system, which was 14.9 ppm in average in Denmark (Groot Koerkamp et al., 1998). The negative pressure in the pit headspace with partial pit ventilations may have prevented the upward air exchange through the slots, hence lowered ammonia concentrations in the pig rooms (Aarnink & Wagemans, 1997; Gustafsson, 1987).

Ammonia concentrations in the room and pit exhaust air increased during the experiment (Fig. 3.5). In all air exhausts, they increased rapidly during the first three days after the pigs were introduced into the rooms, then steadily increased with small fluctuations until the mid of the growing period (day 35). There was a peak at day 13 in pit exhausts when the outdoor temperature was the highest. The data between days 36 and 40 were not included in this paper due to the setting of partial pit ventilation system changed for other research purposes. This change had no effect on the measurements afterwards. From day 41, the concentrations in pit exhausts in both systems increased again. For system C, ammonia concentrations in pit exhaust rose to 21 ppm on day 47, and remained stable with small fluctuations until day 68. It increased again from day 68 and reached the peak of 32 ppm on day 75. For system W, ammonia concentrations in pit exhaust increased to 33 ppm on day 57, then decreased slightly and kept stable with small fluctuations until day 72. The peak value of ammonia concentration in system W pit exhaust was 40 ppm on day 75. Like the overall mean value shown in Table 3.2, the daily mean ammonia concentrations were higher in system W than in system C throughout the whole measuring period (Fig. 3.5).

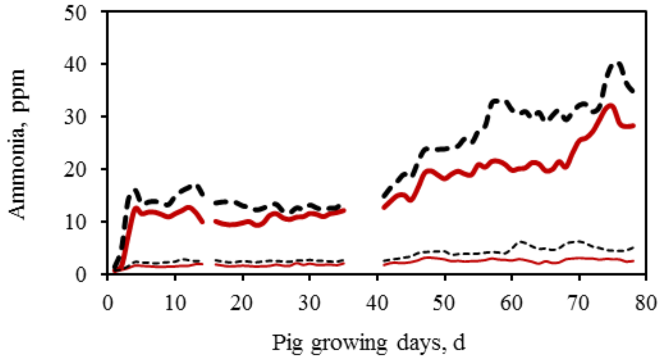

Fig. 3.5 - Daily mean ammonia concentrations at different locations during the pigs' growing period: ▬▬, pit exhaust in system C; ▪▪▪▪▪, pit exhaust in system W; ——, room exhaust in system C; -----, room exhaust in system W.

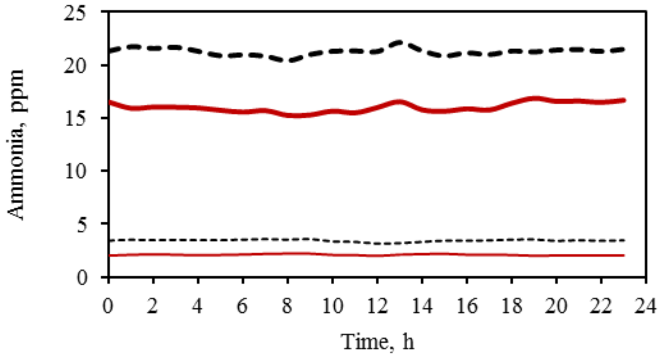

Fig. 3.6 - Mean ammonia concentrations at the same hours of the measuring days: ▬▬, pit exhaust in system C; ▪▪▪▪▪, pit exhaust in system W; ——, room exhaust in system C; -----, room exhaust in system W.

The ammonia concentrations in all exhausts were stable during the 24h day and night cycles, with higher values from system W than from system C (Fig. 3.6). Small variations in the ammonia concentrations at each location were also observed. Ammonia concentrations in room exhaust were higher until 0900 h for both systems, and started to decrease as room ventilation rate increased (Fig. 3.6). When the ventilation rate decreased, ammonia concentrations in room exhaust air climbed again. However, no clear patterns of ammonia concentrations in pit exhaust air were found.

3.3.3. Ammonia emissions

Approximately 48% of the total ammonia emission was from the pit exhaust in system C (Table 3.2). This percentage for system W was 47%. The total ammonia emission was about 22% less in system C than in system W. Higher variation of emission were observed in system W than in system C.

It was found that ammonia emission from all exhausts increased during the experiment (Fig. 3.7). Ammonia emission from room and pit exhausts in system W was higher than those in system C. Emission from the same type of exhausts followed a similar pattern. Higher fluctuations were found in the emission from the room exhausts than from pit exhausts.

The patterns of ammonia emission through pit exhausts were stable during day and night cycles (Fig. 3.8), similar to the patterns of ammonia concentrations. Lower emissions from room exhausts were found in the evening than in the day time. There were broad peaks of emission from room exhausts in the afternoon.

It can be seen from Fig. 3.9 that higher ventilation rates led to increased ammonia emissions in both systems C and W. This was in line with previous studies using different ventilation systems and approaches (Aarnink, Keen, Metz, Speelman & Verstegen, 1995; Aarnink & Wagemans, 1997; Arogo, Zhang, Riskowski, Christianson & Day, 1999; De Praetere & Van Der Biest, 1990; Saha et al., 2010; Ye et al., 2008; Zhang et al., 2008). However, the ammonia emission was lower from system C than from system W, although system W had lower ventilation rates. As mentioned before, the direct supplied air with higher speed in system W could have created turbulence vortices and largely increased ammonia diffusion and release (Ye et al., 2008; Zhang et al., 2008). On average, ammonia emission from room and pit ventilation in system C was 2.91 ± 0.84 g d^{-1} pig^{-1} and 2.72 ± 1.16 g d^{-1} pig^{-1}, respectively. The comparable values for system W were 3.80 ± 1.30 g d^{-1} pig^{-1} and 3.35 ± 1.46 g d^{-1} pig^{-1} for room and pit ventilation, respectively.

The pit ventilation only accounted for 10% of the maximum ventilation rate during summertime. However, almost half of total ammonia emission was from the pit ventilation in the two systems. Polluted air in pit headspace was removed directly by partial pit ventilation before moving up through floor openings and mixing with room air. The exhaust air through the pit outlet could be cleaned effectively by using air purification system. An air cleaning device with bioscrubber reported by Phillips et al. (1999) could abate 97.6% of ammonia from the exhaust air. Applying this kind of air purification system could significantly reduce the total ammonia emission from a pig production unit.

If pit exhaust air was treated by using an effective air purification device (Phillips et al., 1999), the whole fattening period ammonia emission could be reduced to 0.23 kg pig^{-1} and 0.29 kg pig^{-1} for systems C and W, respectively. With only 10% amount of the maximum required ventilation rate being purified, ammonia emission reductions of 46.5% and 47.3% were therefore estimated in systems C and W, respectively.

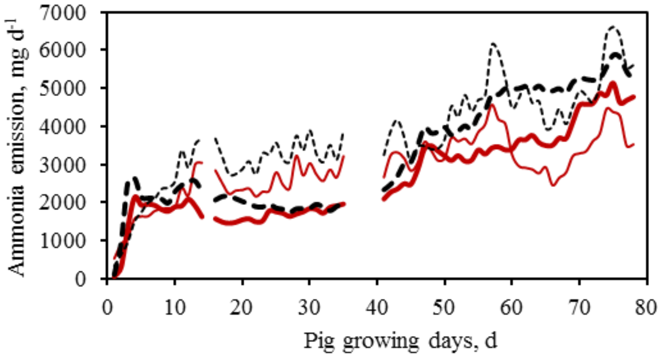

Fig. 3.7 - Daily mean ammonia emissions from different exhausts during the experiment days: ▬▬, pit exhaust in system C; ▪▪▪▪▪, pit exhaust in system W; ——, room exhaust in system C; -----, room exhaust in system W.

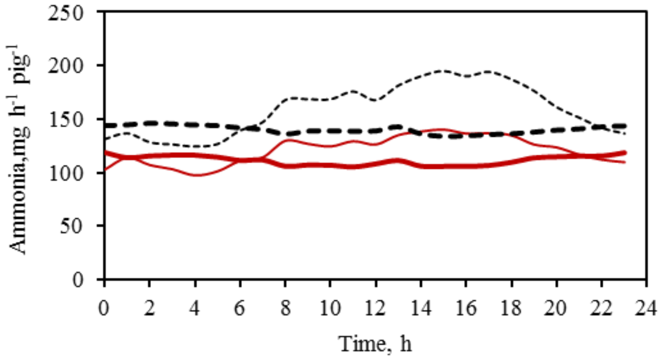

Fig. 3.8 - Mean ammonia emissions at the same hours of the measuring days: ▬▬, system C pit exhaust; ▪▪▪▪▪, system W pit exhaust; ——, system C room exhaust; -----, system W room exhaust.

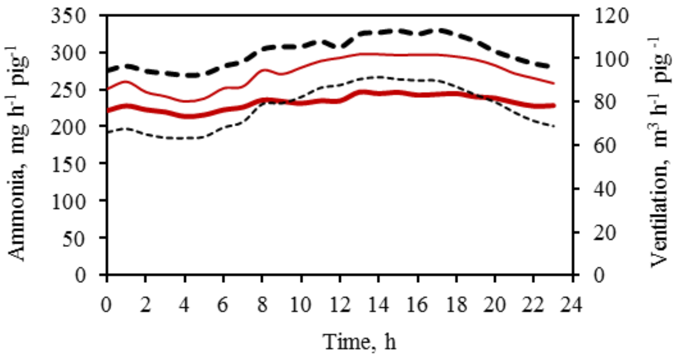

Fig. 3.9 - Mean total ammonia emissions and mean total ventilation rates at the same hours of the measuring period: ▬▬, total emission from system C; ▪▪▪▪▪, total emission from system W; ——, total ventilation rate through system C; -----, total ventilation rate through system W.

3.3.4. Factors affecting the release and dispersion of ammonia

Mean pig active time was 14% in system C and 13% in system W. Fig. 3.10 shows that the pig active time patterns from day to night were very similar for both rooms. They had a narrow peak in the morning and a broad peak in the afternoon. The light manage regimes in both room were light-on from 0700 to 2100 h. During the light-on period, pigs were more active. There was no significant difference in pig active time between the two systems. Animal activity did not contribute the difference of air flow patterns and ammonia concentrations between the two systems.

The slurry channel was partially emptied on day 45 and day 68 for both systems as the manure depth reached 30 cm (Fig. 3.11). It was seen that ammonia concentrations increased rapidly in all exhausts after slurry channels been emptied (Fig. 3.5). The process of emptying slurry channels changed the status of slurry surface, which could create a situation where diffusion paths were shortened and increase the ammonia release (Ni, 1999). Besides, when fresh faeces and urine dropped on the pit bottom, there could be larger renewed slurry surface layer area compared with the situation with stored slurry. This could be the main reason that ammonia concentrations increased rapidly every time the pit was emptied, including the initial period when this experiment just started.

To minimize the difference caused by slurry emptying process between two systems, slurry channels were emptied simultaneously for both systems. However, it was noticed that the slurry depth of one pen in system W increased much faster than other pens in the later stage (Fig. 3.11), which could because pigs in that pen played more with the water trough, and much water dropped into the pit. As the average slurry depths difference between system C and W was bigger, the ammonia concentration difference in pit exhausts became bigger as well (Fig. 3.12). The air exchange rate and mean air velocity above the slurry surface would increase when slurry level rose and got closer to the floor surface (Wu, Zong & Zhang, 2013; Ye, Zhang, et al., 2009). Higher air exchange rate and velocity speed induced more ammonia release from manure (Ni, 1999). Besides, room ventilation rate increased following pigs growing. In the later period, stronger ventilation air motion near floor surface brought higher emission both from floor and slurry surface in pit head space. This is in accordance with the investigations in model pig house with wall jet inlets reported by previous studies (Ye et al., 2011; Zhang et al., 2008).

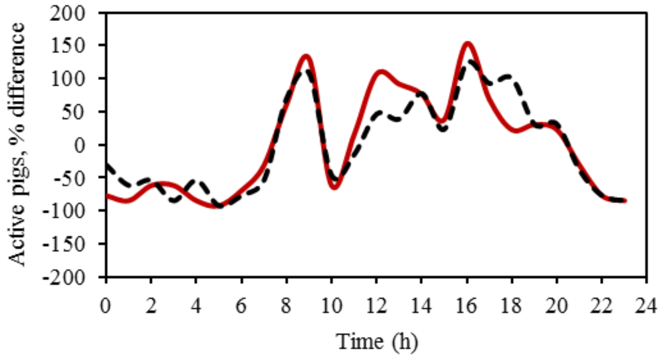

Fig. 3.10 - Mean diurnal pattern of pig activity time (calculated as the percent difference from the daily mean number of pigs not lying) for ventilation systems C and W: ▬▬, pig activity time in system C; ▪▪▪▪▪, pig activity time in system W.

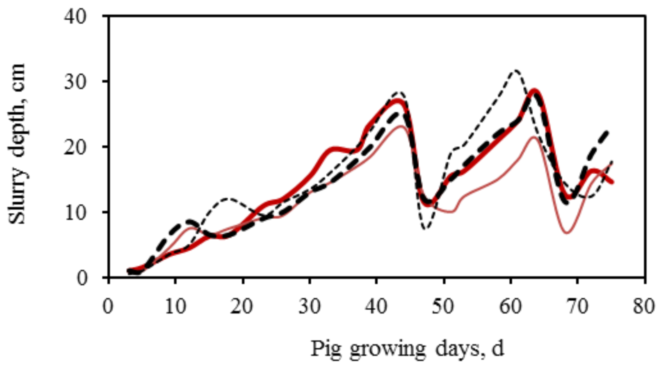

Fig. 3.11 - Slurry depth in different pits during the pigs' growing period: ▬▬, pit 1 of system C; ——, pit 2 of system C; ▪▪▪▪▪, pit 1 of system W; -----, pit 2 of system W.

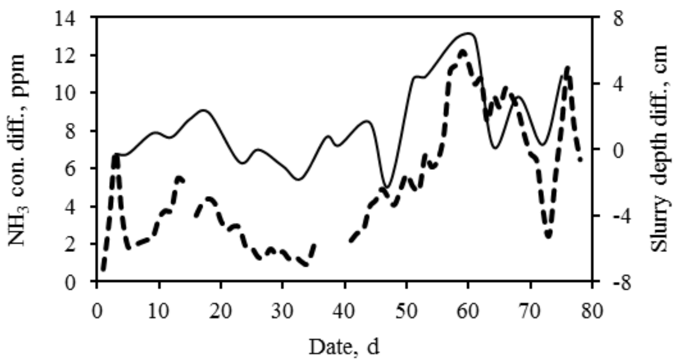

Fig. 3.12 - Ammonia concentration difference in pit exhaust air between system W and system C (system W – system C) (▪▪▪▪▪); and average slurry depths difference between system W and system C (system W – system C) (——) during the pigs' growing period.

Fig. 3.13 shows that room ammonia concentration difference between system C and W decreased, when outside temperature increased. As mentioned above, the outside temperature could also represent the required ventilation rate for both systems (Fig. 3.3). More supplied air was needed under higher outside temperature. The ammonia concentration difference in room air between system C and W decreased as room ventilation requirement increased, which could be caused by the ammonia release rate tend to threshold when high ventilation applied. Air dilution was another reason for this phenomenon.

The ammonia concentration had been always higher in system W than in system C, and the gap of its difference between two systems enlarged in later stage (Fig. 3.5). Ammonia concentration in pig rooms were mainly affected by airflow patterns and air exchange rates between room and pit spaces (Ye, Saha, et al., 2009; Ye, Zhang, et al., 2009). In system W, the outdoor air was directly supplied into the room (Fig. 3.1a). The big return flow of incoming air in system W generated high air velocity and turbulence near the slatted floor (Bjerg, Zhang & Kai, 2008, 2011). This phenomenon made room air easily go through the openings of the slatted floor, and induce high air exchange between the room air and the pit air (Morsing, Strom, Zhang & Kai, 2008; Zhang et al., 2008). Higher mass transportation including ammonia was driven in the exchange air. In addition, the lower ventilation rate required in system W could also contribute to the higher ammonia concentrations due to the smaller dilution rate comparing with system C.

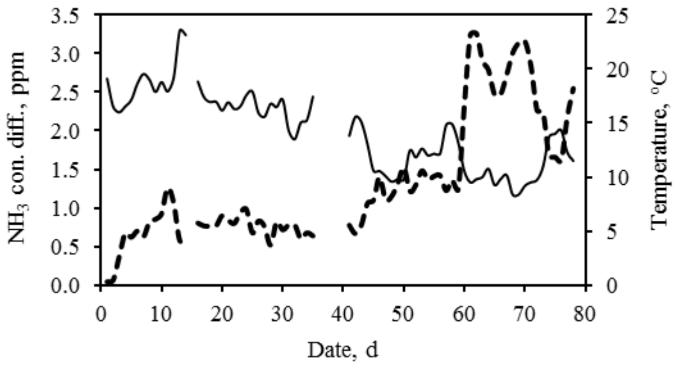

Fig. 3.13 - Ammonia concentration difference in room exhaust air between system W and system C (system W – system C) (▪▪▪▪▪); and outside temperature (——) during the pigs' growing period.

3.3.5. Further discussion and perspective work in future

The research was done in an experimental facility with pigs in summer conditions. It was an early stage research. There were still uncertainties of detailed air movements in animal occupied zone and under the slatted floor. Besides, effects of slurry depth on ammonia emission from pit exhaust and effect of ventilation requirement on ammonia emission from room exhaust need to be investigated in the perspective work. To further evaluate the system performance and generalise emission factors for the partial pit ventilation system, more trials in varied production scales, locations and seasons are needed.

3.4. Conclusion

This experimental investigation regarding partial pit ventilation system in summer conditions has drawn the following conclusions:

Using room ammonia concentration as an indicator, the partial pit ventilation systems with the two investigated inlet configurations and layouts could significantly improve the indoor air quality of a pig room during the summer period compared with a conventional ventilation system. The indoor concentrations were maintained 2.1 and 3.4 ppm in average for systems C and W, respectively.

The ammonia emission from room and pit ventilation in system C was 2.91 g d^{-1} pig^{-1} and 2.72 g d^{-1} pig^{-1}, respectively. The comparable emission values for system W were 3.80 g d^{-1} pig^{-1} and 3.35 g d^{-1} pig^{-1} from room and pit ventilation, respectively. Approximately half of the total ammonia emission was extracted from pit exhausts. If an effective air purification system was applied to clean only the pit exhaust air, significant reduction of ammonia emission could be achieved. The results indicate that the partial pit ventilation can be an efficient technique for reducing ammonia emission together with validated exhaust air purification units.

Ammonia concentration and emission had been always lower in system C than in system W during the fattening period ($p < 0.001$), although the latter required less ventilation rate. The gap of ammonia concentration difference between system C and W enlarged in the later stage. Higher room ventilation rate led to smaller difference of ammonia concentration in room air. Slurry depth played a positive effect on the ammonia emission from pit exhaust. There was no significant difference in the pigs' activity between the two ventilation systems.

Appendix

Feed content:

Earlier stage feed: "dlg Sv Ener Prof Helse U 1kv2012" (dlg a.m.b.a., Copenhagen, Denmark)

21.9% wheat; 20% wheat, torn; 17.5% soybean; 15% barley; 15% barley, torn; 4.9% wheat bran; 2% cane molasses; 1.33% calcium carbonate (chalk); 0.7% coconut fat; 0.45% feed salt; and some vitamins and minerals.

Later stage feed: "dlg Svin Enh Bas Helse U 1kv2012" (dlg a.m.b.a., Copenhagen, Denmark)

40% wheat; 15% barley, torn; 10% barley; 10% rapeseed; 6.4% soybean; 5% wheat bran; 4.1% sunflower seed; 3.3% triticale; 2.5% cane molasses; 1.2% calcium carbonate (chalk); 0.8% coconut fat; and some vitamins and minerals.

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Chapter 4

Carbon dioxide production from a fattening pig building with partial pit ventilation system

Paper III:

Zong, C., Zhang, G., Feng, Y., Ni, J.-Q., 2014. **Carbon dioxide production from a fattening pig building with partial pit ventilation system.** *Biosystems Engineering*, Vol. 126, P 56-68.

Abstract

Carbon dioxide (CO_2) is useful for determining ventilation rates in livestock buildings and its release from manure plays an important role in ammonia emission. CO_2 production in a fattening pig house with a partial pit ventilation system was investigated under working conditions. The influences of animal mass, animal activity, and ventilation rate on CO_2 concentrations and emissions were assessed. Results showed that the CO_2 production rate increased with growing pig body mass. A mathematical model of CO_2 production was developed based on the measured data. The measured CO_2 productions ranged from 30.3 to 99.0 g h^{-1} pig^{-1} for pigs from 30.1 to 111.5 kg. Comparing the last days of the fattening period with and without pigs, it was found that 2.3 to 3.4 % of the total CO_2 production was released from manure. Higher pit ventilation rates resulted in higher CO_2 concentration in pit air and higher emission rates *via* pit exhaust, but had limited influence on the total emission rate (*via* room + pit exhaust). However, higher room ventilation rates resulted in lower CO_2 concentrations in room air but higher room and total emission rates. Diurnal variations in CO_2 productions were mainly influenced by animal activities. Four models of CO_2 production in literatures were reviewed and compared with the model developed in this study. The CO_2 production model developed in this study had similar values with the CIGR model for a pig under 80 kg and the TCER model for a pig above 60 kg.

Keywords: *CO2 production, fattening pig housing, partial pit ventilation, modelling and measurements*

Nomenclature

system C	room with diffusion ceiling/ceiling jet inlets	*TCER*	tranquil CO_2 exhalation rate, g h^{-1}
system W	room with wall jet inlets		
PB	proportional band		
LYD	Danish Landrace × Yorkshire × Duroc	*Subscripts*	
Q	emission/production rate, g h^{-1}	p	total production
V	ventilation rate, m^3 h^{-1}	r	respiration
C	carbon dioxide concentration, g m^{-3}	m	manure release
M	pig body mass, kg	rm	room
F_c	feed consumption, kg d^{-1}	pt	pit
E	metabolisable energy content of feed, J kg^{-1}	tot	total
Φ_{tot}	total heat production, W	re	room exhaust
LU	livestock unit, 500 kg animal mass per LU	pe	pit exhaust
hpu	heat production unit, 1 hpu = 1000 W of total animal heat production at 20 ℃.	in	inlet

4.1. Introduction

Carbon dioxide (CO_2) is one of the most important gaseous contaminants in confinement pig buildings since it is an important parameter for determining indoor quality and a useful tool for calculation of ventilation rate (Estellés, Rodríguez-Latorre, Calvet, Villagrá & Torres, 2010; Feddes & DeShazer, 1988; Ouwerkerk & Pedersen, 1994; Van't Klooster & Heitlager, 1994). Also, CO_2 release influences ammonia release from manure by affecting its pH change (Blanes-Vidal, Guàrdia, Dai & Nadimi, 2012; Blanes-Vidal & Nadimi, 2011; Ni, Hendriks, Vinckier & Coenegrachts, 2000).

Normally, there are two primary sources of CO_2 production in a pig house without combustible heating: animal respiration and manure release. Carbon dioxide produced by animal respiration is a function of energy metabolism rate, which is related to body mass, feeding level and diet nutrient composition, and animal activity (CIGR, 2002; Pedersen et al., 2008). The CO_2 from manure is the gaseous CO_2 released from animal faeces, which are either in the manure pit or on the floor (Ni, Vinckier, Hendriks & Coenegrachts, 1999). Some studies claimed that the quantity of CO_2 released from manure was very small compared with that produced by animal respiration (Anderson, Smith, Bundy & Hammond, 1987; CIGR, 1992; Feddes & DeShazer, 1988; Ouwerkerk & Aarnink, 1992, 1995; Ouwerkerk & Pedersen, 1994; Van't Klooster & Heitlager, 1994). However, other studies found that the quantity of CO_2 from manure release had considerable contribution to the total CO_2 production in fattening pig houses (Ni, Hendriks, Coenegrachts & Vinckier, 1999; Ni, Vinckier, et al., 1999; Pedersen et al., 2008). Pedersen et al. (2008) concluded that the CO_2 produced from manure release varied between houses with different control and management systems. The quantities of CO_2 production in pig houses is mainly affected by the volume, temperature, and age of manure stored in the houses. Biogas produced from stored manure under anaerobic condition consists of about 35 % to 60 % of CO_2 (Deublein & Steinhauser, 2011). To date, only a few studies have determined CO_2 production in pig house using experimental measurements.

Ventilation system and control strategy can significantly influence the airflow characteristics inside a livestock room, which can further influence the emission of gaseous contaminants from animal buildings. A partial pit ventilation system in pig building has recently been developed. It extracts air with the most concentrated gaseous contaminants from the pit headspace directly via pit exhausts and can reduce the gaseous emissions efficiently from the building if the extracted air is treated with an air purification system (Saha, Zhang, Kai & Bjerg, 2010; Wu, Kai & Zhang, 2012; Zong, Feng, Zhang & Hansen, 2014). Nevertheless, no study on CO_2 concentrations in and emissions from the pig building applying such a system has been reported. It is therefore interesting to experimentally investigate the CO_2 production and emission associated with animals and animal manure from the pig building with a partial pit ventilation system.

The objectives of this study are to: (1) investigate the influence of animal mass, ventilation rates and animal activities on CO_2 productions in the building that was equipped with partial pit ventilation system; (2) quantify the CO_2 produced by pig respiration and CO_2 released from manure in the building; (3) develop a mathematical CO_2 production model based on measurement data.

4.2. Materials and methods

4.2.1. Pig house and ventilation

The investigation was carried out in two rooms in an experimental fattening pig house (Fig. 4.1) between 6th August and 23rd October 2012. The dimensions and layout of the house followed the design of typical commercial Danish pig production units. The only difference between the two rooms was its ventilation. One room was equipped with a diffusion ceiling and ceiling jet air inlets (denoted as system C), while another room had wall jet air inlet (denoted as system W) (Fig. 4.1a). The indoor air temperature was controlled at 22 ℃ at the beginning of fattening period for both systems. After 1 week the set-point temperature was decreased linearly until it reached 18 ℃ at the end of the fattening period. To prevent the ventilation control flap from being open and close too frequently, the proportional bands (P-band or PB) of 2.4 and 3.3 ℃ were applied for system C and system W, respectively. There were two pens (4.8 m long and 2.45 m wide) equally divided by a 1-m high partition wall in each room (Fig. 4.1b). The floor areas of all pens were designed with two thirds of slatted floor and one third of drain floor (Fig. 4.1b). The opening ratio of the slatted floor and drain floor was 17.2 % and 8.6 %, respectively. Each pen had a 0.7-m deep manure pit underneath the floor. Manure was pumped out through the valves in the pit bottom when the depth of stored manure was close to or more than 300 mm to avoid manure entering into the pit air exhausts. The manure in the two pits was emptied twice during the experiment.

The experimental building was ventilated by negative pressure ventilation. Systems C and W each had a ceiling-top room exhaust (Fig. 4.1a) and four partial pit exhausts (Fig. 4.2). The capacity of the total ventilation rate of each system was pre-adjusted to 100 m3 h-1 pig-1. The room ventilation rate was automatically controlled by a climate control system (VengSystem, Denmark) based on the indoor air temperature. The pit ventilation rate was fixed at approximately 10 m^3 h^{-1} pig^{-1} throughout the fattening period (10 % of the maximum total ventilation rate) except from days 36 to 40. To study the effect of higher pit ventilation rates on indoor CO_2 concentrations and emission rates, the pit ventilation rates were tested at 20 and 30 m^3 h^{-1} pig^{-1} from days 36 to 38 and from days 38 to 40.

4.2.2. Pigs and feeding

A total of 64 LYD pigs (Danish Landrace × Yorkshire × Duroc) were randomly picked and equally divided for the two systems (32 for each). Feed and water were supplied ad libitum. The pigs were fed with two standard diets for growing-finishing pigs (Table 4.1). One diet was used in the earlier stage. Another diet, which contained higher proportion of fat rapeseed, started on day 32 in the later stage. Straw was supplied on the drain floor area as rooting materials based on Danish regulations.

The pigs were weighed three times during the experiment. The average pig body mass was 30 ± 3.1 kg at the beginning (day 1), 55.1 ± 5.9 kg in the middle (day 31), and 111.8 ± 10.3 kg at the end (day 78) of the experiment. The mean pig growth rate was 1.05 ± 0.13 kg d-1 in system C and 1.08 ± 0.11 kg d-1 in system W (Table 4.2).

Table 4.1 – Composition of the experimental diets

	Earlier peiod diet [a]	Later period diet [b]
Ingredients (%)		
Wheat	21.90	40.00
Wheat, chopped	20.00	-
Soybean meal	17.50	6.40
Barley	15.00	10.00
Barley, chopped	15.00	15.00
Rapeseed	-	10.00
Sunflower meal	-	5.00
Wheat bran	4.90	4.10
Sugar beet molasses	2.00	2.50
Triticale	-	3.30
Calcium cabonate (chalk)	1.33	1.20
Palm fat	0.70	0.80
Vita. lysine liquid	0.47	0.71
Feed salt	0.45	0.42
Monocalcium phosphate	0.40	0.23
Svinevit 437	0.20	0.20
Threonine 98	0.05	0.07
Xylanase	0.05	0.04
DL-Methionine	0.03	-
6-Phytase	0.02	0.03
Nutrition (%) & Energy		
Energy per 100 kg	108 FEsv[b]	104 FEsv[b]
Raw protein	16.4	15.8
Raw fat	3.0	3.8
Raw fibre	3.5	4.6
Raw ash	4.7	4.7
Water	-	14.6

[a] Earlier period feed: "dlg Sv Ener Prof Helse U 1kv2012" (dlg a.m.b.a., Copenhagen, Denmark); [b] Later period feed: "dlg Svin Enh Bas Helse U 1kv2012" (dlg a.m.b.a., Copenhagen, Denmark).
[b] 1 FEsv = 7380 KJ (http://vsp.lf.dk/Viden/Foder/Raavarer/Fodervurdering.aspx).

4.2.3. Measurements

4.2.3.1. Ventilation rates and air flow patterns

Ventilation rates through the room and pit exhaust units were controlled and recorded automatically with a VengSystem (VengSystem, Denmark), and measured every minute by devices for free impeller flow rate measurement (REVENTA® GmbH & Co. KG, Germany), which were pre-calibrated with a coefficient of determination (R^2) of 0.9981.

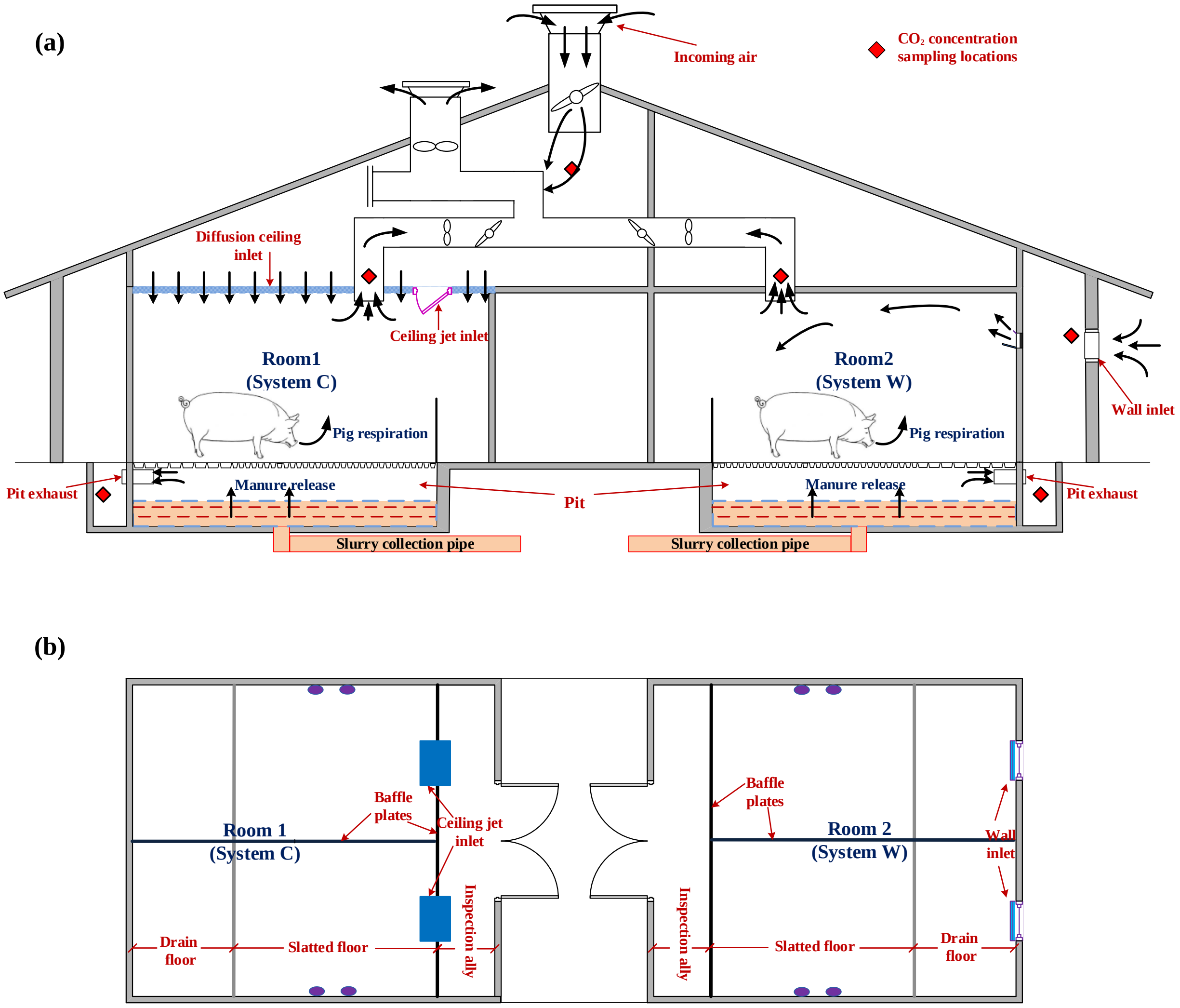

Fig. 4.1 - (a) cross-section of the experimental building and sources of carbon dioxide in the building; (b) floor plan of the investigated building.

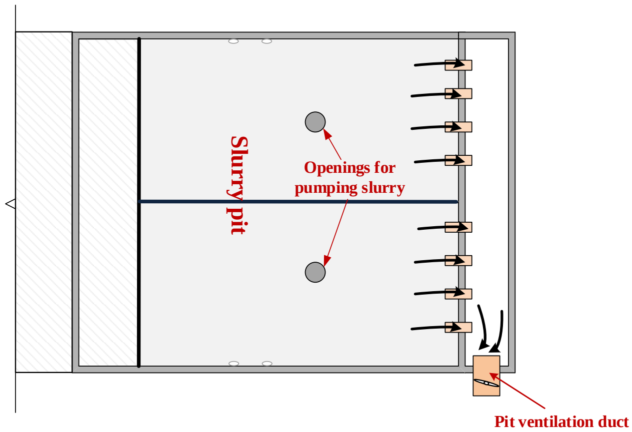

Fig. 4.2 – Floor plan of the pit ventilation underneath the floor in System W (both rooms had the same layout).

Smoke tests were conducted before the pigs were moved into the rooms to observe the air flow patterns under different ventilation systems. A portable smoke generator (Z-series II, Antari Ltd., Taiwan) was used to generate visible smoke particles near the air-inlet units.

Table 4.2 - Performance during the fattening period of two systems of pigs (means ± SD)

	System C (Ceiling inlet)	System W (Wall inlet)
Days	79	79
Number of pigs	32	32
Initial mass (kg)	30.0 ± 2.8 (0.06 LU*)	29.8 ± 3.4 (0.06 LU)
Final mass (kg)	110.8 ± 10.7 (0.22 LU)	112.8 ± 10 (0.23 LU)
Daily mass gain (kg)	1.05 ± 0.13	1.08 ± 0.11
Feed consumption (kg per pig per day)	2.56	2.54
Feed conversion ratio (kg per kg)	2.44	2.35

* 1 LU (livestock unit) = 500 kg animal mass.

4.2.3.2. Carbon dioxide concentration

Air samples were collected from the incoming air, room exhaust air and pit exhaust air in both systems (Fig. 4.1a), and measured continuously with an INNOVA infrared 1412 Photoacoustic Field Multi-Gas Monitor and a 1309 Multipoint Sampler (LumaSense Technologies A/S, Ballerup, Denmark). The calibration of INNOVA Multi-Gas Monitor was conducted by LumaSense Technologies. The ambient temperature and pressure were controlled at 25.1 ℃ and 1007 mbar, respectively, during the calibration. Calibration results showed a standard deviation of 8.76 ppm at a level of 3529.48 ppm carbon dioxide concentration. In this study, the air sampling period for each measurement was 40 s, followed by 20 s flushing time to replace the exhausted air in the measuring chamber and tube of the gas monitor and multipoint sampler before a new measurement started. Six insulated Teflon® tubes (outer diameter 8 mm and inner diameter 6 mm) were installed to connect six sampling locations (Fig. 4.1a) to six inlets of the multipoint sampler, which controlled the timing of sample air collection from different locations and provided the air to the gas monitor. Air from only one sampling location was supplied to the gas monitor at any time. A continuous measurement of 10-min was allocated for each sampling location. Outputs of CO_2 concentrations from the gas monitor were averaged and logged into a personal computer every minute. Thus, ten 1-minute CO_2 concentration measurements were obtained for each sampling location every hour. To reduce the interference of air from different sampling locations during concentration measurement in the gas monitor, the sampling sequence was from locations with low CO_2 concentrations to locations with higher CO_2 concentrations.

4.2.3.3. Air temperature, relative humidity, and manure depth

Temperature and relative humidity (RH) inside both systems and outside the pig building were continuously measured using VE10 and VE14 (VengSystem A/S, Denmark) combined with a measuring probe (HMP50, Vaisala, Finland). The temperature sensor had a range of -50 to 100 ℃ with an accuracy of ±0.2 ℃, while the relative humidity sensor had a range of 0 to 98 % RH with an accuracy of ±3 %. Type T thermocouples connected to a data logger (Eltek Ltd, England) were also used to measure air temperatures (i) in the incoming air: in the attic (air inlet of system C); outside the wall jet inlets of system W, (ii) in both room spaces, one 2 m above the fully slatted floor and the other 2 m above the drain floor of each pen, and (iii) in the pit headspaces. Relative humidity was regularly checked using a Veloci Calc multifunction anemometer (Model 9565, TSI Inc., USA). Manure depths were measured twice a week at a fixed location near the inspection alley in each pit.

4.2.3.4. Pig activity

Pig activities in each pen were monitored automatically with a video monitoring system with infrared cameras (Storage Options Co., China) for the whole experimental period. The recorded videos were used to identify the number of lying pigs and standing pigs. The locations near (i) wall side of slatted floor, (ii) pen partition side of slatted floor, (iii) wall side of drain floor, and (iv) pen partition side of drain floor (Fig. 4.1b) were used to show where pigs preferred to stay. Active pig time was defined as the time when a pig was not lying down (Aarnink & Wagemans, 1997).

4.2.4. Determination of carbon dioxide production and data analysis

The total CO_2 production in this study was the sum of CO_2 produced by the pig respiration, and CO_2 released from the manure. Under steady state, the total CO_2 production rate equals to the total CO_2 emission rate from the pig facility minus the part of CO_2 in the incoming air based on the sys conservation law. The CO_2 production rate and CO_2 respiration rate from pig can be calculated by Eq. (1) and (2), respectively.

$$Q_p = V_{rm}C_{re} + V_{pt}C_{pe} - V_{tot}C_{in} \tag{1}$$

$$Q_r = Q_p - Q_m \tag{2}$$

where Q_p is the rate of CO_2 production, g h^{-1}, V_{rm} the room ventilation rate, m^3 h^{-1}, V_{pt} the pit ventilation rate, m^3 h^{-1}, V_{tot} the total ventilation rate, m^3 h^{-1}, C_{re} the concentration of CO_2 in the room exhaust air, g m^{-3}, C_{pe} the concentration of CO_2 in the pit exhaust air, g m^{-3}, and C_{in} the concentration of CO_2 in the incoming air, g m^{-3}, Q_r the rate of CO_2 from pig respiration, g h^{-1}, Q_m the rate of CO_2 released from manure, g h^{-1}.

It was considered that the mass transfer of CO_2 from the liquid manure to the free air stream inside the pig house was a function of manure contents, air speed on manure surface and manure temperature (Bergman, Incropera, Lavine & DeWitt, 2011; Bird, Stewart & Lightfoot, 2007). The manure composition is related to the manure production which depended on the number of pigs, average pig mass and feed intake. The air speed on the manure surface is related to ventilation rate. The manure temperature is related to indoor air temperature and manure production rate. Under constant ventilation rate and manure temperature, and within a specific period, the CO_2 release rate,

Q_m in equation (2) is therefore assumed unchanged regardless of pigs' presence. Pigs were moved out of the experimental house on day 79. The absence of pigs resulted in the change of CO_2 production rate. Two data sets, one before (days 73-79) and another after (days 79-82) pigs moving out, were compared. They included the CO_2 production rates with and without pigs from the pig house. The data set without pigs was used to calculate the CO_2 release rate, Q_m. The differences of the CO_2 production rates in the two data pairs drove the quantity of CO_2 produced by pigs, Q_r. It should be noted that after pigs moving out, the CO_2 release from manure dropped over time as there was no more fresh manure and drying stored manure. To reduce the impact of the reduction in CO_2 release rate, only 3-days data (days 79-82) with a small reduction of CO_2 release was used for calculation. Thus, when calculating the quantity of CO_2 produced by pigs, the change of CO_2 release from manure was neglected.

Carbon dioxide production per heat production unit (hpu, defined as 1000W of total animal heat production at environmental temperature of 20 ℃) was also introduced in this study for comparison with previous studies (CIGR, 1984, 2002).

Data analysis was done using R (version 3.1.0, R Core Team 2014, www.r-project.org). The single factor ANOVA (analysis of variance) was applied to determine the difference of climate and CO_2 characteristics between the two investigated rooms and the significance of a developed CO_2 production model.

4.3. Results and discussion

4.3.1. Indoor climate characteristics

The mean room air temperatures were significantly higher ($p < 0.001$) in system C (19.2 ± 2.0 ℃) than in system W (18.4 ± 2.0 ℃) (Table 4.3). When fresh air came into system C, it firstly passed through the attic and then passed through the insulated diffusion ceiling. The supply air was warmed up in the insulated attic space. However, for system W, outdoor air came into the room directly through the windows. Consequently, the inlet air was cooler in system W than in system C. The difference was not statistically significant in the daily mean air temperatures measured in the headspace of the manure pits between the two systems ($p > 0.05$). The relative humidity inside both rooms was similar with each other ($p > 0.05$). The highest indoor air temperature and the lowest RH were found between 1600 and 1700h of a day (Fig. 4.3). This was in accordance with the previous study by Ngwabie, Jeppsson, Nimmermark, and Gustafsson (2011).

The room ventilation rate of system C (83.36 ± 16.32 $m^3\ h^{-1}\ pig^{-1}$) was on average 22.3 % higher than that of system W (68.14 ± 19.49 $m^3\ h^{-1}\ pig^{-1}$). To maintain a desired indoor thermal environment, higher room ventilation was required as outdoor temperature increased. Higher fluctuations in the supply air were identified in system W than in system C (Table 4.3). As the setting indoor temperature was the same, a higher ventilation rate was required in system C than in system W.

The smoke tests revealed that, normally, supply air descended slowly and smoothly through diffusion ceiling in system C. When the ceiling jet inlets were open, high speed fresh air was injected into the drain floor area. Almost no air entered the room through the diffusion ceiling. In system W, fresh air through wall jet inlets reached the ceiling first, and travelled around two third of the pen, and then started to descend. There was a large return flow near the animal occupied zone. These air flow patterns agreed with the free jet drop model developed by Zhang, Morsing, and Strom (1996).

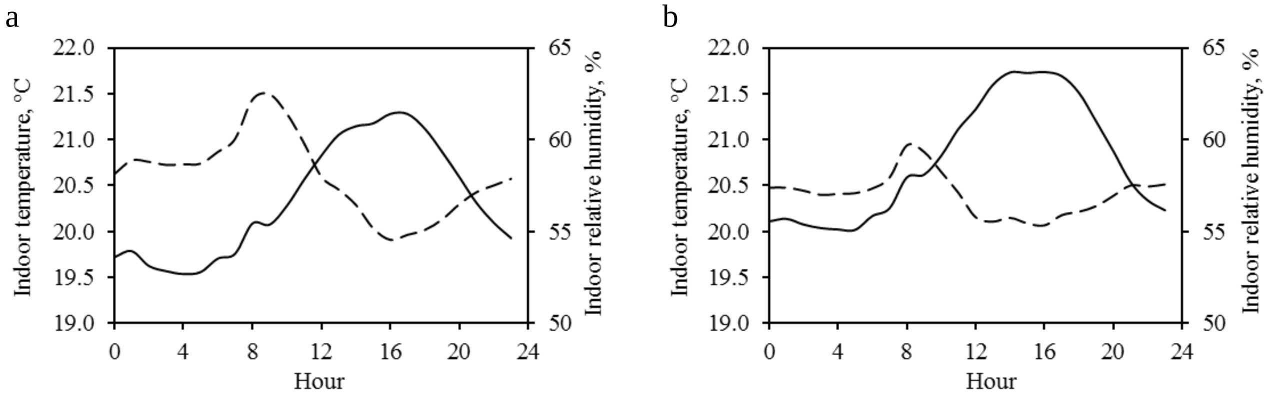

Fig. 4.3. Diurnal pattern (averaged data from the whole fattening period) of temperatures and relative humidity in (a) system C and (b) system W: ——, indoor temperature, ℃; – – –, relative humidity, %. All sensors were located 1.5 m above the floor surface.

Table 4.3 - Means ± standard deviations of temperature and relative humidity in room and pit air, and ventilation rate through room and pit exhausts

Ventilation System	Temperature (℃)		Relative Humidity (%)		Room ventilation rate per pig (m^3 h^{-1} pig^{-1})	Pit ventilation rate per pig (m^3 h^{-1} pig^{-1})
	Room [c]	Pit Headspace	Room [d]	Pit Headspace		
System C [a]	19.2 ± 2.0	20.1 ± 1.7	58.0 ± 6.6	69.8 ± 6.5	83.36 ± 16.32	9.85 ± 0.71
System W [b]	18.4 ± 2.0	20.1 ± 1.5	56.9 ± 5.6	73.9 ± 5.8	68.14 ± 19.49	9.31 ± 0.61
Outdoor	14.3 ± 4.1		76.0 ± 11.9		-	-

[a] System C – room with diffusion ceiling / ceiling jet inlet.

[b] System W – room with wall jet inlet.

[c] 2 m above the floor.

[d] 1.5 m above the floor.

4.3.2. Carbon dioxide concentration and production

Carbon dioxide concentrations were the higher in the pit air than in the room air for both systems (Table 4.4). Between the two systems, system W had higher CO_2 concentrations in both room and pit than system C ($P < 0.001$). The average mean CO_2 concentrations for the two systems were 883 ± 199 ppm in room air, and 1392 ± 394 ppm in pit air.

Table 4.4 - Means ± standard deviations of carbon dioxide concentrations at different locations during the fattening period.

Ventilation System	CO_2 concentration, ppm		
	Room	Pit	Air inlet
System C [a]	800 ± 161	1228 ± 331	443 ± 16
System W [b]	966 ± 199	1556 ± 383	446 ± 18

[a] System C - room with diffusion ceiling / ceiling jet inlet.

[b] System W - room with wall jet inlet.

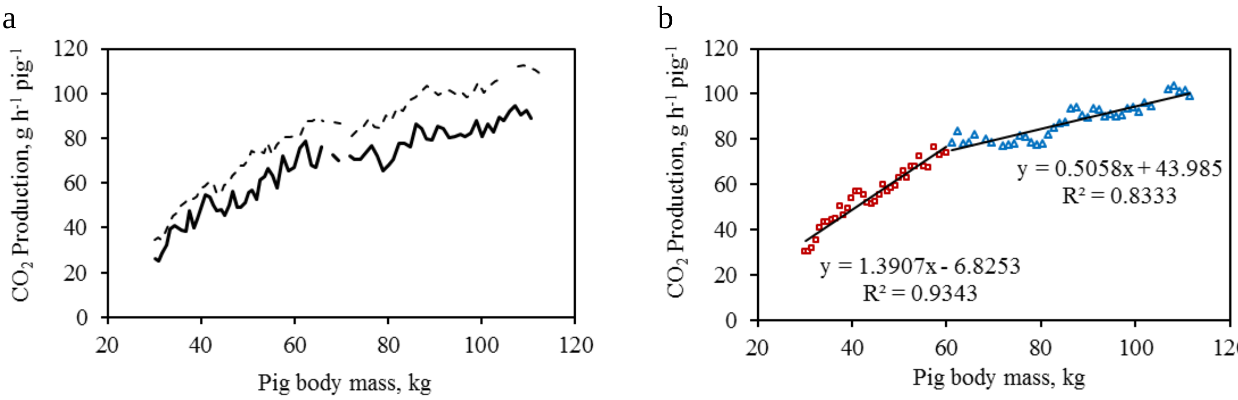

Fig. 4.4. CO_2 production as pigs growing g h^{-1} pig^{-1}. (a), data for system C and system W, separately: ▬▬, system C; ----, system W; (b), integrated data from system C and system W : —□—, 1st period with pig mass below 60 kg; —○— 2nd period with pig mass above 60 kg.

Carbon dioxide production increased throughout the pig fattening period (Fig. 4.4). The quantities of daily CO_2 production were linearly correlated to the average pig mass. The CO_2 production increased faster in the early than in the late of the fattening periods (Fig. 4.4). As a result, the measured CO_2 production rates could be divided into two periods: the 1st period with pig mass under 60 kg and the 2nd period with pig mass above 60 kg. Based on this division, two linear regression equations for the 1st and 2nd periods were established (Fig. 4.4), with R^2 = 0.93 (p < 0.001) and R^2 = 0.83 (p < 0.001), respectively.

$$Q_p = 1.391M - 6.83 \qquad (M < 60) \qquad (3)$$

$$Q_p = 0.506M + 43.99 \qquad (M \geq 60) \qquad (4)$$

Where Q_p is the CO_2 production rate, g h^{-1} and M the average pig body mass, kg.

On average, CO_2 production from system W was 22.1 % higher than that from system C (Fig. 4.4a). This might be partly caused by comparably stronger return airflow, which made pigs more active, in system W. Stronger airflow momentum in system W could also increase the CO_2 release rate either from manure surface or fouling area. However, the measurements in cases without pigs at the end of the investigation showed an opposite result (Fig. 4.5a). Due to the limited tests in this study, the reason for the difference remained unclear. More systematic investigations and measurements are therefore necessary.

Combining all the data from both systems during the fattening period, the average mean CO_2 production was 72.74 ± 25.04 g h^{-1} pig^{-1} for 67.6 kg average pig mass (Table 4.5). The range of CO_2 productions were from 30.3 to 99.0 g h^{-1} pig^{-1} for pigs from 30.1 to 111.5 kg.

4.3.3. Origins of carbon dioxide production

At the end of the fattening period (days 73-79), the mean CO_2 production rate was 91.3 and 108.2 g h^{-1} pig^{-1} in system C and system W, respectively (Fig. 4.5). After pigs moving out, the mean CO_2 release rate was 4.2 and 3.3 g h^{-1} per m^2 of pit surface (77.0-98.9 g h^{-1}) from system C and system W, respectively (Fig. 4.5).

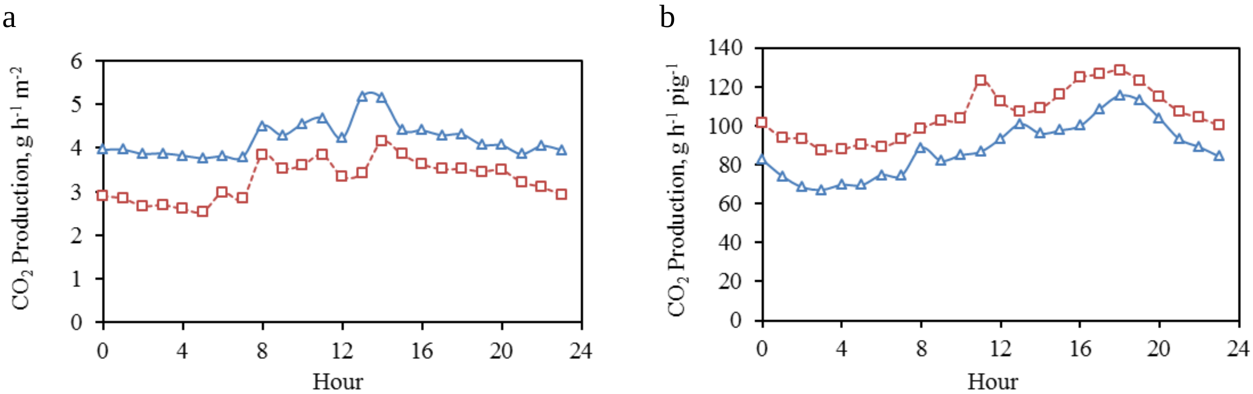

Fig. 4.5. Diurnal pattern (averaged data at the end of the fattening period) of CO_2 produced from (a) manure release, g h^{-1} m^{-2} and (b) pig respiration, g h^{-1} pig^{-1}: —Δ—, system C; —□—, system W.

By comparing CO_2 production rates with and without pigs in the systems at the end of the experiments, the amount of CO_2 production from manure release contributed 3.4 % and 2.3 % of the total CO_2 production in system C and system W, respectively, was obtained. This result was in accordance with several previous studies. Ouwerkerk and Aarnink (1992) calculated that the CO_2 contribution from manure was 2.5 % of the total CO_2 production from pig houses based on theoretical assumptions. In a later study by the same authors (Ouwerkerk & Aarnink, 1995), the CO_2 released from manure was believed to counted 2-4 % of the total CO_2 production in the building. In the study of Ouwerkerk and Pedersen (1994), CO_2 production from manure release was estimated to be 4 % of the total CO_2 production from pig houses. Van't Klooster and Heitlager (1994) assumed that the CO_2 released from stored manure was normally less than 5 % of the quantity emitted from pig respiration. Some research states that the quantity of CO_2 released from manure in pig houses is unimportant (Feddes & DeShazer, 1988) and can even be ignored (CIGR, 1992). However, these studies report data that based on assumptions rather than measurements. Ni, Vinckier, et al. (1999) conducted a measurement study and found the average ratio between the CO_2 released from a 2-m deep under floor manure pit and the CO_2 exhaled from pigs under tranquil conditions was 0.375, which was a significant contribution from manure (27.3 %). In the study of Pedersen et al. (2008), the contribution of CO_2 released from manure to total CO_2 production was estimated to be less than 10 % in the pig houses with regularly removal of manure and good management. Higher CO_2 contribution from manure was believed to happen in buildings where manure was stored over a considerable time period (Pedersen et al., 2008). As a main component in biogas generated from organic waste under anaerobic conditions, the quantity of CO_2 production is related to the manure volume in the pit, the manure temperature, and the freshness of manure (Deublein & Steinhauser, 2011). In this study, the experimental building had a good management and a relatively small manure volume in the pit (manure depth < 0.3 m). The quantity of CO_2 released from manure in this study therefore only made up a small proportion of the total CO_2 production.

4.3.4. Carbon dioxide emission under different ventilation rates

In this part, the CO_2 emissions from either pit or room exhausts were analysed. These emission data was used to better understand the CO_2 production.

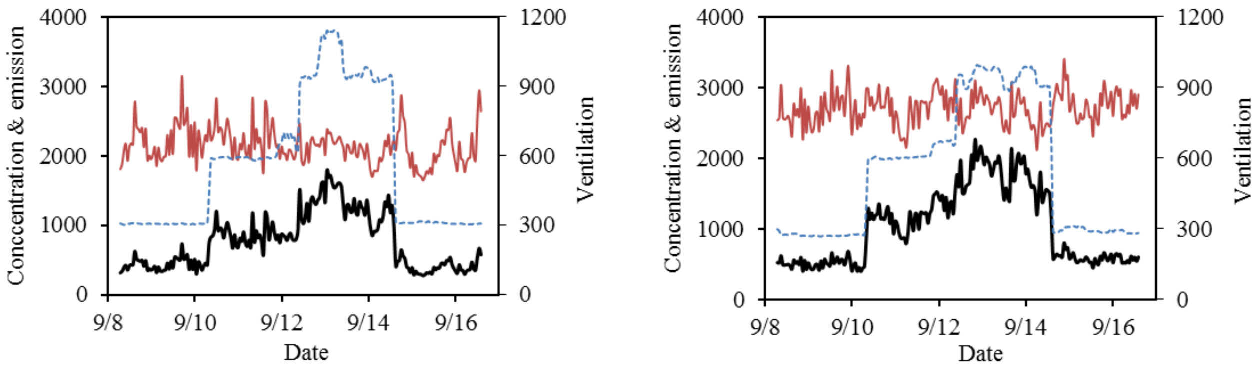

Fig. 4.6. CO_2 concentration and ventilation rate in and emission via pit exhaust for (a) system C and (b) system W. ——, CO_2 concentration mg m^{-3}; ▬▬, CO_2 emission, g h^{-1}; -----, pit ventilation rate m^3 h^{-1}.

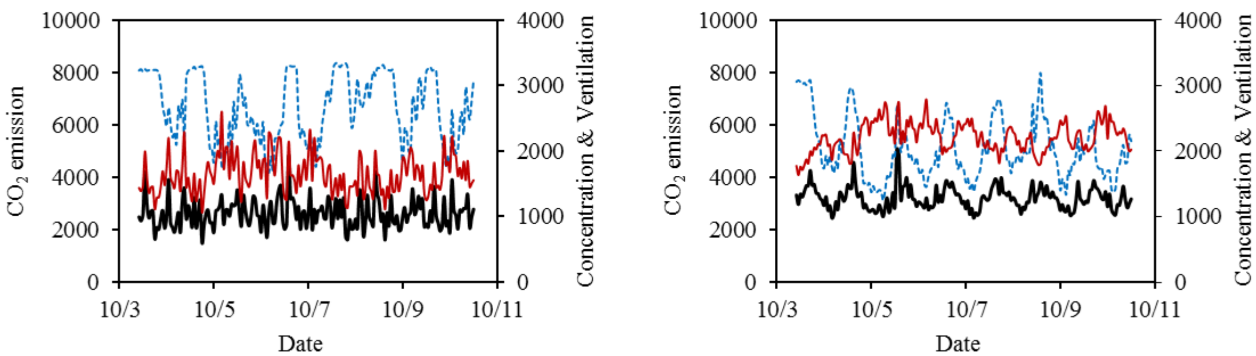

Fig. 4.7. CO_2 concentration in room exhaust air, total CO_2 emission (*via* room + pit exhausts), and total ventilation rates (room + pit) for (a) system C and (b) system W. ——, CO_2 concentration mg m^{-3}; ▬▬, total CO_2 emission, g h^{-1}; -----, total ventilation rate m^3 h^{-1}.

The measured emission *via* pit exhaust under 10 m^3 h^{-1} pig^{-1} pit ventilation (10 % of total ventilation capacity) input was 480 g h^{-1} , while the corresponding value for 20 % and 30 % pit ventilation were 1026 g h^{-1} and 1528 g h^{-1} , respectively (Fig. 4.6). However, no much difference was found for the measured CO_2 concentrations in the pit exhausts air when higher pit ventilation was employed. This was different from the results of Ni, Vinckier, et al. (1999), in which application of a pulse ventilation in a mechanically-ventilated room without pigs induced both higher CO_2 concentration and emission. At the same time, the total emission (*via* room + pit exhaust air) under 10 % pit ventilation input was 2361 g h^{-1}, while the corresponding value for 20% and 30% pit ventilation were 2575 g h^{-1} and 2548 g h^{-1}, respectively.

Normally, pit ventilation was fixed at 10 m^3 h^{-1} pig^{-1} (10 % of total ventilation capacity), while the room ventilation varied between day and night, as the outdoor temperature was much lower at night than during the day time. Figure 7 shows the influence of the variation of total ventilation rate (room + 10 %-pit ventilation) on the total CO_2 emission (*via* room + pit exhaust air) and CO_2 concentration in room exhaust air. The total CO_2 emission generally followed the pattern of total ventilation rate (Fig. 4.7). Pigs are less active at night (CIGR, 2002), which can result in the decrease in CO_2 production. The CO_2 concentration in the room exhaust air had an opposite pattern compared with the total ventilation rate (Fig. 4.7). Higher ventilation rate could remove more air from the building and dilute the gaseous contaminant concentrations (Zong et al., 2014). Consequently, the observed CO_2 concentration in room air was higher at night and lower in day time.

4.3.5. Effect of animal activity

The pig heat and CO_2 productions are correlated to animal activities (Van't Klooster & Heitlager, 1994).In current study, this correlation is demonstrated in Fig. 4.8 ($p < 0.001$), in which CO_2 production increases when pigs are more active. There were a narrow peak in the morning and a broad peak in the afternoon. The morning and afternoon peaks were probably caused by the natural behaviour of the pigs during eating, urinating, defecating, rooting, etc. (Ngwabie et al., 2011). In this study, the pigs were more active during the light-on period, which was from 0700 to 2100 h, compared with the light-off period.

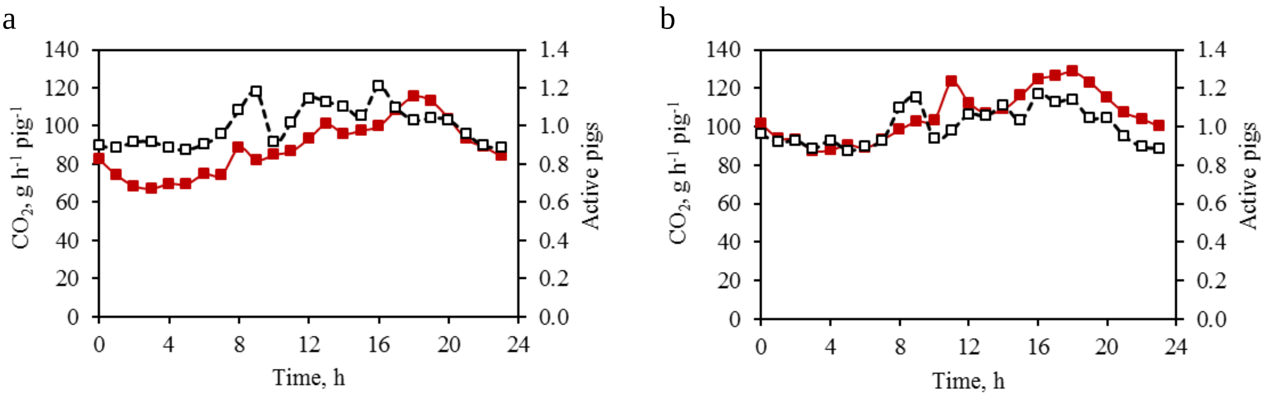

Fig. 4.8. Production of CO_2 versus animal activity: – –□– –, relative activity, —■—, CO_2 production in (a) system C and (b) system W.

The mean pig active time was 14 % and 13 % in system C and system W, respectively. The pigs were lying on the floor around 86.5 % of the time during the observation days. On average 38 % of the pigs were lying on the wall side of the drained floor, 29 % on the pen partition side of the drained floor, 22 % on the wall side of the slatted floor, and 11 % on the pen partition side of the slatted floor (for location see Fig. 4.1b). The fact that pigs preferred to lie on the drained floor (opening ratio: 8.5 %) instead of the slatted floor (opening ratio: 16.5 %) agreed with previous studies that pigs preferred to lie on a solid insulated floor rather than lie on a slatted floor (Fraser, 1985; Saha et al., 2010). Lower air exchange in the area like drain floor may provide better comfort zones to pigs. Higher CO_2 concentrations could exist in this area with higher animal density and lower air exchange rate. More investigations on CO_2 distribution need to be conducted in further study.

4.3.6. Comparison of carbon dioxide production with previous studies

Carbon dioxide productions were 0.210 and 0.248 $m^3\ h^{-1}\ hpu^{-1}$ from system C and system W at the final fattening period (days 73-79), respectively. The average CO_2 production from a pig house with partial pit ventilation system was 0.206 $m^3\ h^{-1}\ hpu^{-1}$. Table 4.5 summarises the CO_2 productions of current and previous studies (Blanes & Pedersen, 2005; Philippe, Laitat, Canart, Vandenheede & Nicks, 2007). The quantities of CO_2 production from a fattening pig building with fully slatted floor were similar (Table 4.5).

The recommended reference value for CO_2 production for the ventilation flow calculation by CIGR was 0.163 $m^3\ h^{-1}\ hpu^{-1}$ in 1984 which was updated to 0.185 $m^3\ h^{-1}\ hpu^{-1}$ in 2002 (CIGR, 1984, 2002). Ouwerkerk and Pedersen (1994) estimated that the total CO_2 production in animal houses was between 0.17 and 0.20 $m^3\ h^{-1}\ hpu^{-1}$, and on average of 0.185 $m^3\ h^{-1}\ hpu^{-1}$. Sousa and Pedersen (2004) stated that using total CO_2 production of 0.185 $m^3\ h^{-1}\ hpu^{-1}$ for calculation got the same level ventilation rates with measured value. However, Blanes and Pedersen (2005) concluded that the total CO_2 production of 0.201 $m^3\ h^{-1}\ hpu^{-1}$ could result in better agreement with measured ventilation flow rate. A value of 0.202 $m^3\ h^{-1}\ hpu^{-1}$ was calculated from the reported data of Philippe et al. (2007). In the studies of Ni, Heber, and Lim (2008) and Ngwabie et al. (2011), the CO_2 production was up to 0.254 and 0.266 $m^3\ h^{-1}\ hpu^{-1}$. The variation in CO_2 production mainly resulted from differences in animal species, body mass, the feeding level, and control strategy and management at a house level (Pedersen et al., 2008).

4.3.7. Comparison with other models of carbon dioxide production

A graphic comparison of the CO_2 production calculated by the model of Eq. (3) and Eq. (4) with other three reported models is illustrated in Fig. 4.9. All of these models were taken as a function of either the pig mass or feed consumption, which converted to pig mass as well (CIGR, 2002; Feddes & DeShazer, 1988; Ni, Hendriks, et al., 1999; Van't Klooster & Heitlager, 1994).

Ni, Hendriks, et al. (1999) developed a tranquil CO_2 exhalation rate (TCER) model based on measured data in relation to body mass from 32 to 105 kg. The CO_2 production model (Eq. (5)) was the sum of TCER and the CO_2 produced from manure release, which was 37.5% of TCER (Ni, Vinckier, et al., 1999).

$$Q_p = 280.137\ M^{0.46} \quad (5)$$

where Q_p is the CO_2 production rate, g d^{-1} and M the pig body mass, kg.

Feddes and DeShazer (1988) established the relationship of feed consumption and CO_2 production. A simplified model was derived for finishing pigs (Eq. (6)).

$$Q_p = 306\ F_c \quad (6)$$

where F_c is the feed consumption, kg d^{-1}.

Table 4.5 - Comparison of CO_2 production rates in fattening pig houses with slatted floor in this study and from the literature.

Pig mass, kg		CO_2 production			In-house	Source
Range	Average	g h^{-1} pig^{-1}	g d^{-1} LU^{-1} [a]	m^3 h^{-1} hpu^{-1} [b]	manure storage	
30 to 110	67.3	65.8	12.2	0.187	0.7-m deep pit [e]	System C
30 to 60	44.4	49.4	13.3	0.178	0.7-m deep pit [e]	System C
60 to 110	85.4	78.6	11.2	0.199	0.7-m deep pit [e]	System C
-	110.9	88.2 [c]	9.6 [c]	0.203 [c]	0.7-m deep pit [e]	System C
-	110.9	91.3 [d]	9.9 [d]	0.210 [d]	0.7-m deep pit [e]	System C
30 to 110	67.8	79.7	14.1	0.226	0.7-m deep pit [e]	System W
30 to 60	44.2	60.2	16.2	0.217	0.7-m deep pit [e]	System W
60 to 110	86.4	95.1	13.4	0.240	0.7-m deep pit [e]	System W
-	112.8	105.7 [c]	11.2 [c]	0.242 [c]	0.7-m deep pit [e]	System W
-	112.8	108.2 [d]	11.5 [d]	0.248 [d]	0.7-m deep pit [e]	System W
30 to 110	67.6	72.7	13.4	0.206	0.7-m deep pit [e]	Systems C & W
30 to 60	44.3	54.8	14.8	0.197	0.7-m deep pit [e]	Systems C & W
60 to 110	85.9	86.8	12.3	0.220	0.7-m deep pit [e]	Systems C & W
-	-	-	-	0.163	-	CIGR (1984) [f]
-	105	73.9 [c] 101.6 [d]	8.4 [c] 11.6 [d]	0.173 [c] 0.232 [d]	2-m deep pit	Ni *et al.* (1999)
-	-	-	-	0.185	-	CIGR (2002) [f]
-	-	-	-	0.201	-	Blanes and Pedersen (2005)
-	67.8	72.5	12.8	0.202	0.45-m deep pit	Philippe *et al.* (2007)
-	64.4 63.6	91.4 75.1	17.5 14.2	0.266 0.220	Shallow flushing gutters	Ni *et al.* (2008)
-	60.1-69.5	84-91	15.7-16.9	0.254	1.2-m manure gutters	Ngwabie *et al.* (2011)

[a] 1 LU (livestock unit) = 500 kg animal mass.

[b] 1 hpu (heat production unit) = 1000 W of total animal heat production at 20 ℃.

[c] CO_2 production from pigs only.

[d] CO_2 production from pigs and manure.

[e] the manure depth was kept < 0.3 m to avoid manure pouring into the pit air exhausts.

[f] theoretical value, not from direct measurement.

Table 4.6 - Live body mass, heat production and CO_2 production based on CIGR (2002) report

Live mass, kg	Maintenance, MJ d^{-1}	Daily feed intake [a], W	Total heat production, W	CO_2 production [b]		
				$l\ h^{-1}$	$g\ h^{-1}\ pig^{-1}$	$g\ d^{-1}\ pig^{-1}$
30	5.64	212.05	129.84	24.02	43.94	1054.48
40	6.99	277.69	161.62	29.90	54.69	1312.54
50	8.27	326.36	183.36	33.92	62.05	1489.09
60	9.48	373.09	201.91	37.35	68.32	1639.74
70	10.64	418.81	217.78	40.29	73.69	1768.68
80	11.76	460.21	230.13	42.57	77.87	1868.95
90	12.85	472.96	233.03	43.11	78.85	1892.51
100	13.91	479.66	234.26	43.34	79.27	1902.50
110	14.94	480.63	234.43	43.37	79.33	1903.91

[a] daily feed intake was calculated based on the rate of gain = 900 g/day in Denmark (CIGR, 2002).
[b] carbon dioxide production is fixed at 0.185 $m^3\ h^{-1}$ per hpu (heat production unit, 1 hpu = 1000 W of total heat at 20 ℃).

Table 4.7 - Comparison of measured and modelled CO_2 production

Growing stage	Live mass, kg	CO_2 production, $g\ h^{-1}\ pig^{-1}$					Reference
		Measured value	M1[a]	M2[b]	M3[c]	M4[d]	
Final	105	73.9 [e]	-	72.2	-	-	Ni et al.
		101.6 [f]	97.1	99.3	84.7	69.9	(1999)
Averaged	67.8	72.5	78.3	81.2	61.9	51.7	Philippe et al. (2007)
Averaged	64.4	91.4	76.6	79.3	59.6	50.0	Ni et al.
	63.6	75.1	76.2	78.8	59.1	49.5	(2008)
Final	110.9	88.2 [e]	-	74.1	-	-	System C
		91.3 [f]	100.1	101.8	88.3	72.6	
Final	112.8	105.7 [e]	-	74.6	-	-	System W
		108.2 [f]	101.1	102.6	89.1	73.5	
Averaged	67.6	72.7	78.2	81.1	61.7	51.7	System C & W

[a] model of this work.
[b] model of Ni et al. (1999a).
[c] model of Van't Klooster and Heitlager (1994).
[d] model of Feddes et al. (1991).
[e] CO_2 production from pigs only.
[f] CO_2 production from pigs and manure.

The feed consumption was dependent on the pig mass which could be calculated by Eq. (7) which was derived by Ouwerkerk and Aarnink (1992).

$$\mathrm{F}_c = 0.122\, M^{0.688} \tag{7}$$

The model developed by Van't Klooster and Heitlager (1994) was a function of pig mass, feed consumption, and metabolisable energy content in feed (Eq. (8)).

$$\mathrm{Q}_p = 84600(3.33 \times 10^{-7} M^{0.75} + 3.28 \times 10^{-13} F_c \cdot E) \tag{8}$$

where E is the metabolisable energy content of feed, J kg^{-1}, which was taken as 12.8 MJ kg^{-1} in Fig. 4.9.

A CO_2 production model (Eq. (10)) can be derived from heat production model (Eq. (9)) developed in CIGR (2002) combined with the recommended carbon dioxide production value of 0.185 m^3 h^{-1} hpu^{-1}.

$$\Phi_{tot} = 5.09M^{0.75} + [1 - (0.47 + 0.003M)][n \times 5.09M^{0.75} - 5.09M^{0.75}] \tag{9}$$

$$\mathrm{Q}_p = 8.131\, \Phi_{tot} \tag{10}$$

where Φ_{tot} is total heat production, W; n represents the daily feed energy intake, expressed as n times the maintenance requirement. The CO_2 production based on CIGR (2002) report is presented in Table 4.6.

The calculated results from these models with pig mass from 30 to 110 kg show a clear disparity among each other (Fig. 4.9). Our model had a very close value as the models of Feddes and DeShazer (1988) and Van't Klooster and Heitlager (1994) at the beginning. The CIGR (2002) model calculated similar values with our model for a pig between 40 and 80 kg, and had a same calculation result at 50 kg. For a pig above 60 kg, our model produces the similar values with the model developed by Ni, Hendriks, et al. (1999).

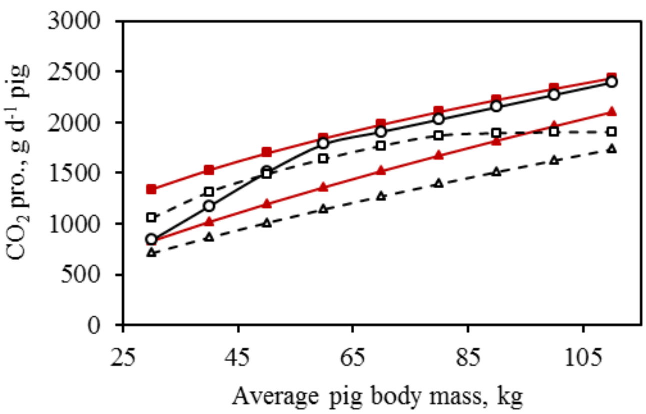

Fig. 4.9. Comparison of mean daily carbon dioxide production rate (g d^{-1} pig^{-1}) of different models. Note: —○—, model of this work; —■—, model of Ni et al., (1999a); – –□– –, model of CIGR (2002); —▲—, model of Van’t Klooster and Heitlager (1994); – –Δ– –, model of Feddes et al. (1991).

These models were also used for calculation of the measurements in this and previous studies (Table 4.7). The results calculated from models of Feddes and DeShazer (1988) and Van't Klooster and Heitlager (1994) were much lower than the measurement results. The calculated results from the model of our study and the model developed by Ni, Hendriks, et al. (1999) are generally consistent with the measured values (Table 4.7).

4.4. Conclusion

Based on the experimental study in the fattening pig building with partial pit ventilation, the following conclusions were made:

- The total CO_2 production from pig house increased proportionally as the pigs grew.
- From the data of the last days of fattening period, the quantity of CO_2 released from manure consisted 3.4 % and 2.3 % of the total CO_2 production in system C and system W, respectively.
- The higher pit ventilation rate resulted in higher CO_2 concentration in pit exhaust air and higher emission rate via pit exhaust, but had limited influence on the total emission rate (*via* room + pit exhaust). With a fixed pit ventilation rate, the higher room ventilation rate resulted in lower CO_2 concentration in room exhaust air and higher room and total emission rate.
- The diurnal variations in CO_2 production were mainly influenced by animal activity, which had a diurnal pattern with a narrow peak in the morning and broad peak in the afternoon.
- The average CO_2 production was 72.7 g h^{-1} pig^{-1} or 0.206 m^3 h^{-1} hpu^{-1}, which was close to previous studies.
- The CO_2 production model developed in this study produced similar values to the CIGR model for a pig under 80 kg and the Ni's TCER model for a pig above 60 kg.

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Chapter 5

Ammonia and greenhouse gas emissions from fattening pig house with two types of partial pit ventilation systems

Paper IV:

Zong, C., Li, H., Zhang, G., 2014. **Ammonia and greenhouse gas emissions from fattening pig house with two types of partial pit ventilation systems**. *Submitted to a peer review journal*.

Abstract

Intensive pig production is an important source of polluting gases emissions like ammonia (NH_3) and greenhouse gases (GHG). To minimize their negative impacts on ecosystems and environments, the emissions have to be reduced. Among various reduction techniques that under development, air purification system using multi-stage scrubber is one with very high-efficiency. However, it is very expensive to treat large amount of exhaust air using air purification system. Consequently, partial pit ventilation (PPV) extracting air with high gas concentration from emission source zone has therefore been developed.

In this study, the performance of the PPV in two pig production units with different room ventilation air inlets was investigated: (1) with ceiling air inlet, system-C and (2) with wall jet air inlet, system-W. Two trials in both summer and winter periods were carried out. Each trial covered an entire production period from 30-110kg pig^{-1}. Each experiment unit consisted of 2 pig pens and 32 fattening pigs. The maximum ventilation rate was set as 100 m^3 h^{-1} pig^{-1}. Room ventilation rate was automatically controlled to maintain a set indoor temperature, while pit ventilation rate was fixed to maintain at 10% of the maximum ventilation rate. Gaseous concentrations and emissions were continuously measured in air inlet, room exhaust, and pit exhaust for both PPV systems.

Results showed that the average indoor concentrations were maintained 2.1-3.4 ppm (for NH_3), 0.4-0.6 ppm (for CH_4), and 800-966 ppm (for CO_2) in summer; and 4.2-4.3 ppm (for NH_3), 5.0-5.6 ppm (for CH_4), and 1491-1542 ppm (for CO_2) in winter. There were almost no N_2O releases found in current set-up. Using indoor NH_3 concentrations as an indicator, the PPV system could significantly improve indoor air quality, which can benefit both working environment and animal welfare. Approximately half of the whole NH_3 emission (47-63%) was extracted from pit exhausts. As only removing pollutants from the pit exhaust, the capacity of an air purification system will be considerably reduced. Combination of PPV and air purification system can be a practical and efficient mitigation method for reducing gaseous pollution from pig production. In this study, gas emissions during fattening period were mainly influenced by the different air-inlets and seasonal times. The two types of PPV systems resulted in two different kinds of airflow characteristics, which further affected the gaseous release process. Higher ventilation rate was required for system-C than for system-W to keep a same setting indoor temperature. Lower gases concentrations were observed in system-C than in system-W during summer. During winter, gases concentrations were higher in room air and a little lower in pit air from system-C than from system-W. Gas concentrations in room were higher during winter than during summer. The daily mean NH_3 emissions were lower, while the daily mean CH_4 and CO_2 emissions were higher, during winter than during summer.

Keywords: *Ammonia, Greenhouse gases, emission, fattening pig, partial pit ventilation*

5.1. Introduction

Intensive pig production contributes significantly to emissions of ammonia (NH_3) and greenhouse gases (GHG), which have a number of negative impacts on surrounding environment and climate (Cabaraux et al., 2009; Hutchings, Sommer, Andersen & Asman, 2001; Philippe, Laitat, et al., 2011).

Emissions of NH_3 to the atmosphere are implicated in soil acidification and eutrophication of aquatic ecosystems (Krupa, 2003). Furthermore, NH_3 is well known as a toxic gas, which represents potential health hazards to both human beings and animals inside the animal house (Banhazi, Seedorf, Rutley & Pitchford, 2008; Donham, 1991). According to Hutchings et al. (2001), nearly 99% of the total NH_3 emissions in Denmark were from agricultural sources, while emissions from pig housing accounted for 34% of agricultural emissions.

Emissions of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), are connected with global warming and climate change. CO_2, originating from animal respiration and manure, is an important gas in confined livestock buildings. The production of CO_2 has been used as key parameter for ventilation rate estimation (Feddes & DeShazer, 1988). CH_4 and N_2O are important contributors to greenhouse effect as their global warming potential (GWP) over a 100-year period are, respectively, 25 and 298 times that of CO_2 (Intergovernmental Panel on Climate Change, 2007). In addition, N_2O also causes the loss of the ozone layer.

Reducing NH_3 and GHG emissions have been an important goal by international regulations for a long term (United Nations Economic Commission for Europe, 2013).

Gaseous formation and volatilization can be influenced by many different factors: animals, (e.g. genetics, diet, number and weight, animal activity, and behaviour), animal wastes (e.g. storage methods, treatment, pH, temperature, and surface area), ventilation (control strategy, temperature, flow rate, and air velocity above manure surface) and other site-specific factors(Blanes-Vidal, Hansen, Pedersen & Rom, 2008; Haeussermann, Hartung, Gallmann & Jungbluth, 2006). An optimal control of those influencing factors can help to reduce gaseous emissions from livestock productions. Regarding the factor of ventilation, mechanical ventilation is one of the most common control and mitigation methods for gaseous pollution from livestock production (Cho, Ko, Kim & Kim, 2012). A very high efficient way using mechanical ventilation to eliminate those polluted gaseous is the employ of air purification system (e.g. air scrubber) at air exhausts (Philippe, Cabaraux & Nicks, 2011; Zhao, Aarnink, de Jong, Ogink & Koerkamp, 2011; Zucker, Scharf, Kersten & Müller, 2005). However, it is quite expensive because of high investment and operation costs related to energy, chemical and filter consumption and maintenance for both ventilation and purification systems (Melse, Ogink & Rulkens, 2009). One proposed strategy to reduce the costs is cleaning only a partial amount (10% of maximum ventilation rate) of exhaust air extracted from the main source zone where highly concentrated air pollutants originate from (Saha, Zhang, Kai & Bjerg, 2010; Zong, Feng, Zhang & Hansen, 2014). A partial pit ventilation (PPV) system with an extra pit exhaust under slatted floor has therefore been developed. Besides, employing a PPV system could remove the gases and odours from the pit space above the manure surface before convection airflow and turbulences transfer the gases up to the room space, and significantly improve indoor air quality (Saha et al., 2010). And consequently both working environment and animal welfare are also improved.

In Denmark, negative pressure ventilation systems with ceiling-roof top exhaust units incorporated either diffuse ceiling inlet or wall-flap inlet are conventionally used in fattening pig housing. However, up until now, few data is available about gaseous emissions from fattening pig housing with a PPV system combined with these two common types of mechanical ventilation systems. The NH_3 emission regarding this has been investigated in a pilot study (Zong, Feng, et al., 2014), but other gases were not included and it was only in summer condition.

Thus, the objectives of this study were (1) to quantify gaseous emissions in fattening pig housing with a partial pit ventilation system; (2) to investigate the effects of using ceiling and wall air inlets as well as winter and summer seasons on gaseous emissions; and (3) to analyse the feasibility of partial pit ventilation system in pig housing.

5.2. Materials and methods

Two trials were carried out in experimental pig production units located at Research Centre Foulum of Aarhus University, Denmark. The first trial was conducted in a summer condition between 6th August and 23rd October 2012, and the second one was during winter period from 18th November 2013 to 18th February, 2014.

5.2.1. Experimental rooms

Two identical rooms of the experimental pig house, with dimensions of 5.7 × 4.9 × 2.67 m ($L \times W \times H$), were arranged and equipped for this experiment (Fig. 5.1). The dimensions and layout of the house followed a section of typical commercial Danish pig production housing. The room was equally divided into two pens (4.8 × 2.45 m, $L \times W$) by a 1-m high partition wall (Fig. 5.1b). Each pen had two thirds fully slatted floor and one third drain floor (Fig. 5.1b). Drain floor was a type of slatted floor with smaller slot openings. Here, opening ratio of the fully slatted floor and drain floor was 17.2% and 8.6%, respectively. Underneath the floor, a 0.7-m deep manure pit was built for each pen. Manure could be pumped out through the valves in the pit bottom. To avoid manure pouring into the pit air exhausts, the depth of stored manure was kept under 0.3 m during experiment. Above the floor, two drinking troughs were attached on the side wall, and one feeder was on the partition wall for each pen (Fig. 5.1b). There was a 1.2-m wide inspection alley. This pig house was designed to facilitate laboratory tests of various ventilation systems and operation strategies.

5.2.2. Ventilation systems

A central outlet duct with two ventilators (REVENTA ® GmbH & Co. KG, Germany) was installed near the building ridge (Fig. 5.1a) to create negative pressures for rooms. All exhaust units were connected to this central outlet duct. Airflow rate in each exhaust unit was regulated by an analogue controlled damper (VengSystem A/S, Denmark) inside the exhaust unit (a sub-duct) (Fig. 5.1a).

The same layout of exhaust units was equipped for both rooms: a ceiling-top room exhaust and a partial pit exhaust. As the major air outlet, room exhaust unit was a 0.46-m diameter chimney duct mounted an impeller anemometer in the duct (Fig. 5.1a). The anemometer was accompanied with a frequency converter (VengSystem A/S, Denmark) to measure airflow rate created by the central outlet duct and regulated damper. Room ventilation rate was automatically controlled by the VengSystem based on indoor thermal conditions during the experiment. Pit exhaust unit was located under the drain floor (Fig. 5.1c). Each pen had four 0.16-m diameter pit exhaust pipes installed on the side wall. These pipes extracted the exhaust air from pit headspace into a ventilation duct, which could further connect to an air purification system for treatment (Fig. 5.1c). Airflow rate through pit ventilation duct was also measured by an impeller anemometer and a frequency converter inside duct (VengSystem A/S, Denmark). Instead of automatic control, pit ventilation rate was kept at approximately 10% of the maximum total ventilation rate during the experiment. As a result, the analogue controlled damper (VengSystem A/S, Denmark) in pit ventilation duct was fixed during the experiment. The maximum ventilation rate was pre-adjusted as 3200 $m^3 h^{-1}$. A set-point temperature of 22 ℃ was applied at the beginning of each fattening period for both systems. After 1 week the set-point temperature was decreased linearly until reaching 18 ℃ at the end of each fattening period.

The only difference between the two rooms was the air inlets. One room was equipped with a diffusion ceiling and ceiling jet air inlets (system-C), while another room had wall jet air inlet (system-W) (Fig. 5.1a).

5.2.2.1. System-C

System-C applying diffusion ceiling and ceiling-jet air inlets plus partial pit and ceiling-top exhausts was operated in Room 1 (Fig. 5.1). Under negative pressure, fresh air first entered the Room 1 attic *via* three 0.8-m diameter air ducts on the building ridge, and then went through the diffusion ceiling into room space. The diffusion ceiling was made of porous materials consisted of compressed straw plate and mineral wool isolation layer. Two ceiling-jet air inlets (0.62 × 0.24 m) facing downward the drain floor area were installed in the ceiling. Normally, those ceiling-jets were closed. When room temperature increased to 22.8 ℃, the ceiling-jet flaps would open to increase the air speed in animal occupied zones (AOZ). A proportional control was used in the ventilation control and the proportional band (P-band) of 2.4 ℃ was set for regulating airflow control-flap.

5.2.2.2. System-W

System-W with wall-jet air inlets plus partial pit and ceiling-top exhausts was operated in Room 2 (Fig. 5.1). Two wall-jet air inlets with bottom hinged flap (0.62 × 0.24 m) and top guiding plate (0.62 × 0.03 m) were installed on the sidewall. Both wall-jets were placed 1.83-m above the floor in a symmetrical plan of a pen. The opening size of wall-jet inlet was regulated automatically together with room exhaust ventilation rates (VengSystem A/S, Denmark). A P-band of 3.3 ℃ was set for system-W. The top guiding plate was designed to guide the inlet air direction, which was obliquely upward with an angle of 40 degrees to horizontal plane during this experiment.

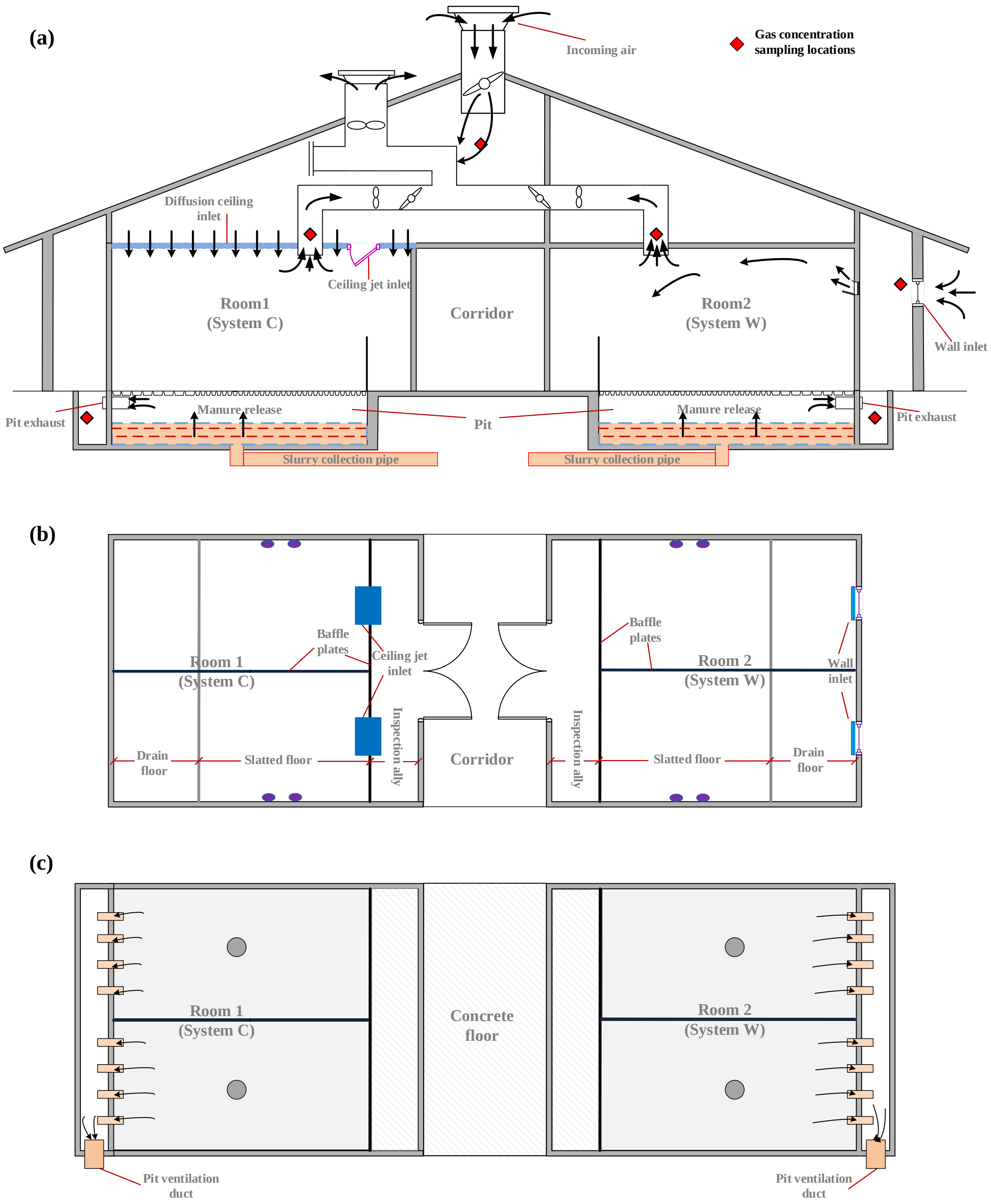

Fig. 5.1 – (a) cross-section and (b) floor plan of the experimental rooms; (c) pit ventilation system under the floor.

5.2.3. Animals and feed

For each trial and in each type of PPV system, 32 Danish Landrace × Yorkshire × Duroc (LYD) weaned pigs were raised. They were randomly picked and equally divided into two pens according to the sex and the body weight.

Feed and water were supplied *ad libitum*. Two types of standard diets for growing-finishing pigs were used during each fattening batch. Pigs were given a commercial growing diet, followed after about 30 d by a finishing diet (Table 5.1). The diets were same for the two systems. The pigs were weighed individually at the beginning (1 d), in the middle (31 d), and at the end (77 d) of each experimental trial. Straw was supplied on the drain floor area as rooting materials based on Danish regulations.

Table 5.1 – Composition of the experimental diets

	Summer		Winter	
	Earlier peiod diet [a]	Later period diet [b]	Earlier peiod diet [c]	Later period diet [d]
Ingredients (%)				
Wheat	21.90	40.00	35.00	25.00
Wheat, chopped	20.00	-	-	-
Soybean meal	17.50	6.40	9.80	5.00
Barley	15.00	10.00	10.00	7.50
Barley, chopped	15.00	15.00	15.00	15.00
Rapeseed	-	10.00	-	10.00
Rye	-	-	9.00	19.80
Oats	-	-	4.60	5.00
Sunflower meal	-	5.00	8.00	8.00
Wheat bran	4.90	4.10	3.00	-
Sugar beet molasses	2.00	2.50	1.00	1.00
Triticale	-	3.30	-	-
Calcium cabonate (chalk)	1.33	1.20	1.26	1.14
Palm fat	0.70	0.80	1.40	0.80
Vita. lysine liquid	0.47	0.71	0.76	0.70
Feed salt	0.45	0.42	0.44	0.45
Monocalcium phosphate	0.40	0.23	0.36	0.27
Svinevit 437	0.20	0.20	0.20	0.20
Threonine 98	0.05	0.07	0.09	0.07
Xylanase	0.05	0.04	0.04	0.05
DL-Methionine	0.03	-	0.02	-
6-Phytase	0.02	0.03	0.03	0.02
Energy & Nutrition (%)				
Energy (FEsv[e])	108	104	104	103
Crude protein	16.4	15.8	15.1	15.6
Crude fat	3.0	3.8	3.6	3.2
Crude fibre	3.5	4.6	4.9	5.4
Crude ash	4.7	4.7	4.7	4.6
Water	-	14.6	14.4	9.2

[a] Earlier period feed: "Sv Ener Prof Helse U 1kv2012" (dlg a.m.b.a., Copenhagen, Denmark);
[b] Later period feed: "Svin Enh Bas Helse U 1kv2012" (dlg a.m.b.a., Copenhagen, Denmark).
[c] Earlier period feed:"Svin Enhed Classic Helse U 2013"(dlg a.m.b.a., Copenhagen, Denmark);
[d] Later period feed: "Svin Enhed Ideal Helse U 2013" (dlg a.m.b.a., Copenhagen, Denmark);
[e] 1 FEsv = 7380 KJ (http://vsp.lf.dk/Viden/Foder/Raavarer/Fodervurdering.aspx).

Table 5.2 - Performance during the fattening period of two systems of pigs (means ± SD)

	Summer (6 Aug. to 23 Oct. 2012)		Winter (18 Nov. 2013 to 18 Feb. 2014)	
	System C (Ceiling inlet)	System W (Wall inlet)	System C (Ceiling inlet)	System W (Wall inlet)
Raising duration (d)	79	79	93	93
Number of pigs	32	32	32	32
Initial weight (kg)	30.0 ± 2.8	29.8 ± 3.4	29.6 ± 1.6	29.6 ± 1.1
weight after raising 30 d (kg)	55.2 ± 5.5	55.0 ± 6.4	50.7 ± 4.4	49.7 ± 4.6
Final weight (kg)	110.8 ± 10.7	112.8 ± 10.0	121.0 ± 9.1	118.0 ± 12.3
Average daily weight gain (kg)	1.05 ± 0.13	1.08 ± 0.11	0.99 ± 0.1	0.92 ± 0.26
Feed intake (kg per pig per day)	2.56	2.54	2.93	2.91
Feed conversion ratio (kg per kg)	2.44	2.35	2.96	3.16

5.2.4. Measurements

5.2.4.1. Ventilation rates and air flow patterns

Ventilation rates *via* exhaust units were measured every minute by flow measurement device (REVENTA® GmbH & Co. KG, Germany) and recorded automatically by the VengSystem (VengSystem, Denmark). The flow measuring device was pre-calibrated with a R^2 of 0.998.

To observe the air flow patterns, smoke tests using a portable smoke generator (Z-series II, Antari Ltd., Taiwan) were conducted before pigs moving into the experimental rooms.

5.2.4.2. Gaseous pollutants concentrations

The concentrations of gases in the two systems were continuously measured with an apparatuses from LumaSense Technologies (INNOVA infrared 1412 Photoacoustic Field Multi-Gas Monitor and 1309 Multipoint Sampler), which were pre-calibrated for the measurement of NH_3, N_2O, CH_4, CO_2. Air samples were collected from the incoming air, room exhaust air and pit exhaust air in each system (Fig. 5.1a). Six insulated Teflon tubes (outer diameter 8 mm and inner diameter 6 mm) were used to connect the six sampling locations (Fig. 5.1a) to six channels of the 1309 Multipoint Sampler, which further sent the sample air to the Multi-Gas Monitor. Air from only one channel of the Multipoint Sampler was supplied to the Multi-Gas Monitor at any time. For every measurement, the sampling air was analysed 40 s, followed by 20 s flushing time to replace air in the analysing chamber before a new measurement started. Ten minutes were allocated for each sampling location. Therefore, ten 1-minute concentration data were obtained for each sampling location every hour.

5.2.4.3. Air temperature, relative humidity, and manure depth

Temperature and relative humidity inside both systems and outside the pig building were continuously measured using VE10A and VE14 Sensors (VengSystem A/S, Denmark). A Veloci

Calc multifunction anemometer (Model 9565, TSI Inc., USA) was used to check temperature and relative humidity regularly. Manure depth in each pit was measured twice a week at a fixed location near the inspection alley.

5.2.5. Calculation of emission rate and statistical analysis

For each gas, the emissions were calculated on an hourly basis using the following equation:

$$E_{gas} = V_r C_{re} + V_p C_{pe} - V_{tot} C_{in} \quad (1)$$

where E_{gas} is the gas emission rate, mg h^{-1}, V_r the room ventilation rate, m^3 h^{-1}, V_p the pit ventilation rate, m^3 h^{-1}, V_{tot} the total ventilation rate, m^3 h^{-1}, C_{re} the concentration of gas in the room exhaust air, g m^{-3}, C_{pe} the concentration of gas in the pit exhaust air, g m^{-3}, and C_{in} the concentration of gas in the incoming air, g m^{-3}.

Data analysis was done using R (version 3.1.0, 2014 The R Foundation for Statistical Computing). The single factor ANOVA (analysis of variance) was applied to determine the effects of the two types of air inlets on climate and gaseous characteristics.

5.3. Results

5.3.1. Animal performance

The animal performance is shown in Table 5.2. The raising duration of the winter trial was two weeks longer than that of summer trial. The mean initial body weight was around 30 kg for all cases. On average, pigs gained more weight and consumed less feed daily in summer than in winter. For each season, the average daily weight gains (ADG) were not significantly different with pigs kept either in system-C or system-W.

5.3.2. Climate characteristics

5.3.2.1. Air temperature and relative humidity

The indoor and outdoor air temperatures, relative humidity, and ventilation rates *via* pit and room exhausts during measurement periods are presented in Table 5.3. The indoor air temperatures stayed stable as its automatic adaption with the room ventilation rates. Although the indoor set-point temperatures were the same for both trials, the average temperatures of indoor air were a little lower in winter period due to cooler outdoor air. There was no significant difference of indoor air temperatures between system-C and system-W during the same season ($p < 0.01$). The relative humidity was lower in winter than summer season.

5.3.2.2. Ventilation rate

The room ventilation rates of system-C were on average 22.3% and 16.0% higher than that of system-W ($p < 0.001$) on average during summer and winter period, respectively (Table 5.3). To maintain the set indoor thermal environment, higher room ventilation was required as outdoor temperature increased (Fig. 5.3). Pit ventilation rates were kept at a same level around 10 $m^3 h^{-1} pig^{-1}$ (Table 5.3).

5.3.2.3. Airflow pattern

The smoke tests revealed that, normally, supplied air dropped down slowly and smoothly through diffusion ceiling in system-C (Fig. 5.2). When the ceiling-jet inlets were open in summer, high speed fresh air was injected into the drain floor area. There was almost no air went into the room through diffusion ceiling at that situation. In system-W, fresh air from wall-jet inlets reached the ceiling first and travelled some distance, and then started to drop (Fig. 5.2). There was a large return flow near the animal occupied zone. These air flow patterns agreed with the free jet drop model developed by Zhang, Morsing, and Strom (1996). Small proportion of short circuiting of incoming air to room exhaust openings occurred in both systems.

Table 5.3 - Means ± standard deviations of temperature and relative humidity in room and pit air, and ventilation rate through room and pit exhausts

	Summer		Winter	
	System C	System W	System C	System W
Room air temperature [a] (℃)	20.33 ± 1.52	20.77 ± 1.55	19.44 ± 0.36	19.45 ± 0.40
Outside temperature (℃)	14.3 ± 4.1		5.06 ± 3.14	
Room air relative humidity [a] (%)	58.0 ± 6.6	56.9 ± 5.6	50.44 ± 5.32	54.01 ± 4.90
Outside relative humidity (%)	76.0 ± 11.9		74.08 ± 8.32	
Room ventilation rates ($m^3 h^{-1} pig^{-1}$)	83.36 ± 16.32	68.14 ± 19.49	28.06 ± 15.63	24.19 ± 11.55
Pit ventilation rates ($m^3 h^{-1} pig^{-1}$)	9.85 ± 0.71	9.31 ± 0.61	9.16 ± 0.73	9.88 ± 0.78

[a] 1.5 m above the floor

5.3.3. Gas concentrations

Table 5.4 summarizes the mean and standard deviation of the gas concentrations at different locations.

Much higher ammonia concentrations were observed in pit air than in room air. In summer, the mean NH_3 concentration at room and pit exhausts was respectively 63.8% and 28% higher in system-W than in system-C($p < 0.001$). However in winter, the mean NH_3 concentration at room and pit exhausts was 3.6% and 9.5% lower in system-W than in system-C, respectively ($p < 0.001$). The NH_3 concentrations in the incoming air were quite low.

The mean N_2O concentrations were almost the same in all exhausts and incoming air. N_2O concentrations in all exhaust air stayed at around 0.32-0.35 ppm throughout the each fattening periods.

Outdoor concentrations of CH_4 were undetectable. Higher concentrations were observed in pit air than in room air. In summer, very low CH_4 concentrations were observed in room exhausts air both in system-W and system-C. System-W had higher mean CH_4 concentration than in system-C both at room and pit exhausts ($p < 0.001$). In winter, CH_4 concentrations were higher in room air but lower

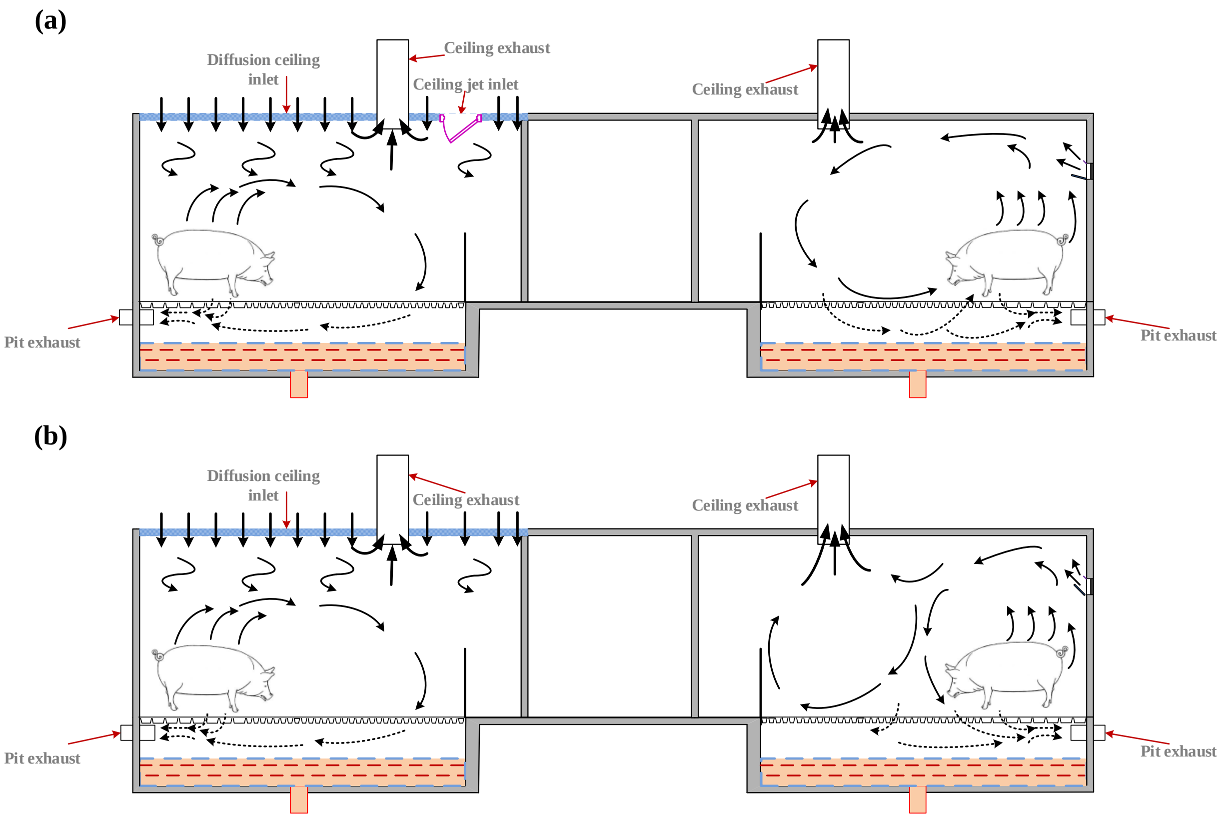

Fig. 5.2 – General airflow patterns in system-C (left) and system-W (right) during (a) summer and (b) winter, respectively.

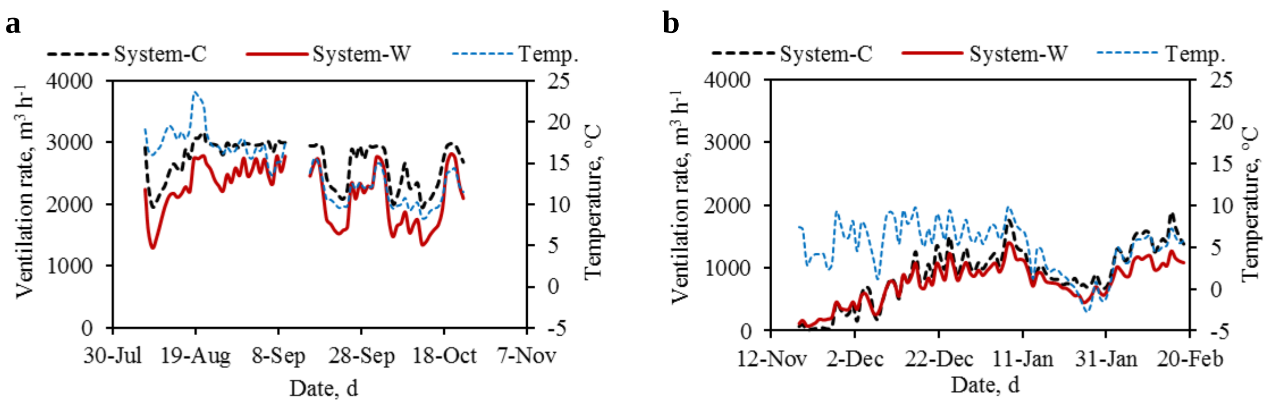

Fig. 5.3 - Daily mean temperatures and ventilation rates during the pigs' growing period: ▪▪▪▪▪▪, room ventilation rate in system C; ▬▬, room ventilation rate in system W; ⋯⋯, outside temperature.

in pit air for system-C than for system-W. The mean CH_4 concentrations were much higher in winter than in summer. The mean CH_4 concentrations demonstrated seasonal variations for both systems.

Table 5.4 - Means ± standard deviations of gaseous concentrations at different locations

Gas	Exhaust / inlet	Summer		Sig.[a]	Winter		Sig.[a]
		System C	System W		System C	System W	
NH_3 concentration, ppm	Room exhaust	2.10 ± 0.69	3.44 ± 1.36	***	4.32 ± 1.36	4.17 ± 1.72	NS
	Slurry-pit exhaust	16.62 ± 6.73	21.27 ± 9.06	***	16.27 ± 8.41	17.82 ± 7.38	***
	Air inlet	0.58 ± 0.15	0.45 ± 0.13	***	0.34 ± 0.15	0.32 ± 0.07	***
N_2O concentration, ppm	Room exhaust	0.33 ± 0.02	0.33 ± 0.02	*	0.32 ± 0.02	0.32 ± 0.02	NS
	Slurry-pit exhaust	0.34 ± 0.03	0.35 ± 0.03	***	0.34 ± 0.03	0.33 ± 0.03	NS
	Air inlet	0.33 ± 0.02	0.33 ± 0.02	NS	0.33 ± 0.02	0.33 ± 0.02	**
CH_4 concentration, ppm	Room exhaust	0.38 ± 0.55	0.60 ± 0.67	***	5.60 ± 2.52	5.00 ± 3.78	***
	Slurry-pit exhaust	5.42 ± 3.91	6.53 ± 3.90	***	14.35 ± 9.89	15.14 ± 9.66	*
	Air inlet	0.00 ± 0.01	0.00 ± 0.01	NS	0.00 ± 0.01	0.00 ± 0.01	NS
CO_2 concentration, ppm	Room exhaust	800 ± 161	966 ± 199	***	1542 ± 258	1491 ± 321	***
	Slurry-pit exhaust	1228 ± 331	1556 ± 383	***	1856 ± 455	2229 ± 497	***
	Air inlet	443 ± 16	446 ± 18	***	463 ± 14	458 ± 12	***

Sig.: significance; NS: not significant;
* p<0.05;
** p<0.01;
*** p<0.01.

The mean CO_2 concentrations were higher in pit air than in room air. In summer, system-W had higher CO_2 concentrations in both room and pit air than system-C ($p < 0.001$). However in winter, only the mean CO_2 concentration in pit exhaust air was higher in system-W than in system-C ($p < 0.001$); and the concentrations in room air were slight higher in system-C than in system-W ($p < 0.01$). The outdoor concentrations of CO_2 were kept around 450 ppm.

5.3.4. Gas emissions

Table 5.5 summarizes the mean gaseous emissions from different systems in summer and winter. Fig. 5.4 shows the emissions from the beginning to the end for each fattening period.

In summer, approximately 48% and 47% of the NH_3 emission was extracted from the pit exhaust in system-C and system-W, respectively (Table 5.5). The NH_3 emission was about 22% less in system-C than in system-W. In winter, more than half of the NH_3 emission was from the pit exhaust (53% and 63% for system-C and system-W, respectively). System-C and system-W have similar amount of daily total NH_3 emission. It was found that NH_3 emission increased during each fattening period (Fig. 5.4).

As the N_2O concentrations were more or less the same in all exhausted and incoming air (Table 5.4), N_2O emissions were negligible.

In summer, the primary CH_4 emission was via pit exhausts. The amount of total daily CH_4 emission was about 35.1% less in system-C than in system-W. In winter, CH_4 emissions from pit exhaust and room exhaust were similar. Approximately 7.1% higher CH_4 emission was found in system-C than in system-W (Table 5.5). CH_4 emission increased with some drops during each fattening period (Fig. 5.4).

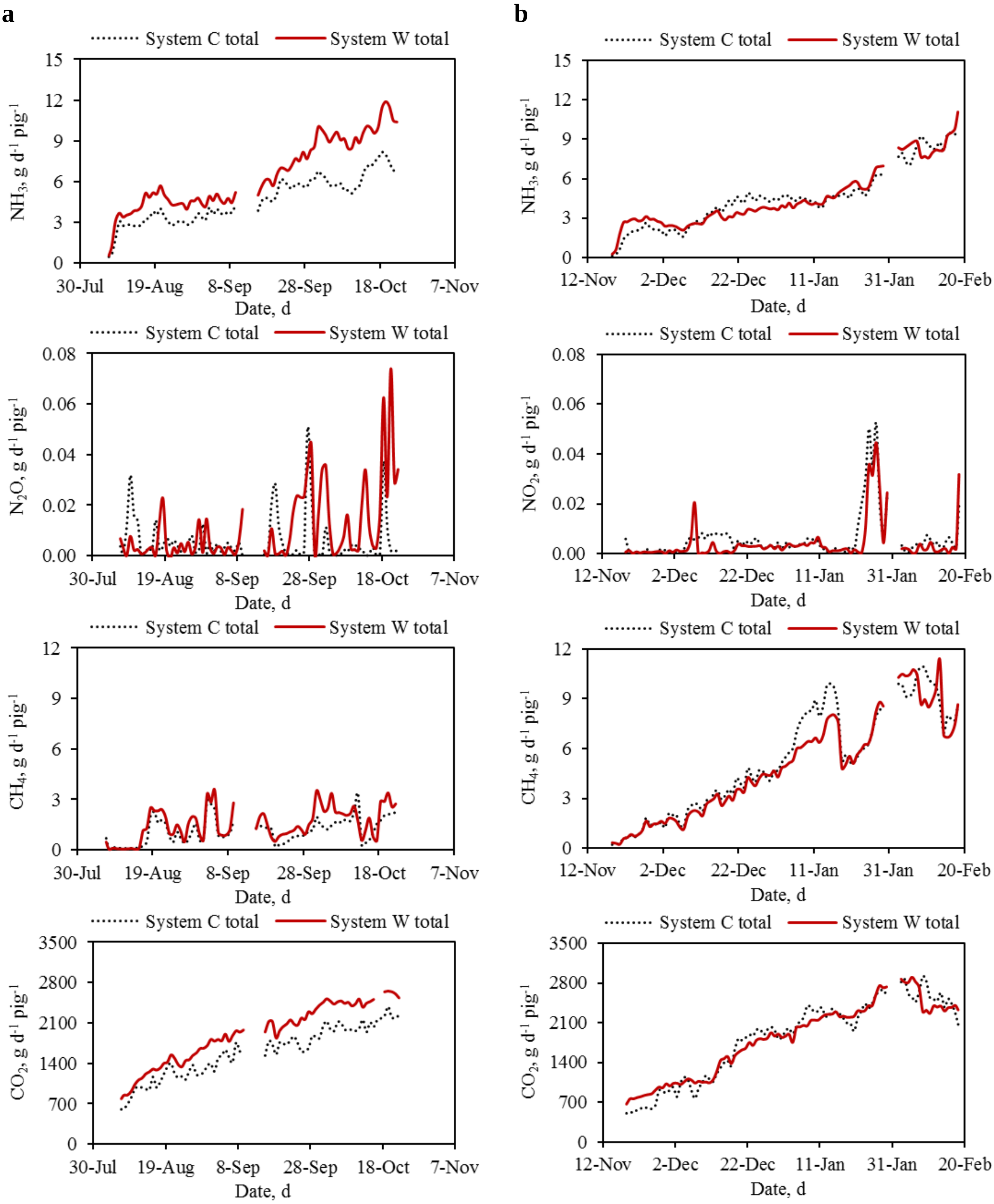

Fig. 5.4 - Daily mean gaseous emission rates per pig during the fattening periods under system-C and system-W: (a) summer condition and (b) winter condition.

Table 5.5 - Means ± standard deviations of gaseous emissions through room and pit exhausts

		Summer		Sig.[a]	Winter		Sig.[a]
		System C	System W		System C	System W	
NH_3 emissions, g d^{-1} pig^{-1}	Through room exhaust	2.90 ± 0.98	3.81 ± 1.50	***	2.19 ± 1.43	1.72 ± 1.14	***
	Through pit exhaust	2.68 ± 1.15	3.36 ± 1.48	***	2.49 ± 1.16	2.99 ± 1.35	***
	Total	4.67 ± 1.75	6.55 ± 2.61	***	4.57 ± 2.33	4.59 ± 2.30	NS
N_2O emissions, g d^{-1} pig^{-1}	Through room exhaust	0.00 ± 0.02	0.00 ± 0.02	NS	0.00 ± 0.03	0.00 ± 0.02	NS
	Through pit exhaust	0.00 ± 0.00	0.01 ± 0.01	**	0.00 ± 0.01	0.00 ± 0.01	NS
	Total	0.01 ± 0.01	0.01 ± 0.01	*	0.01 ± 0.01	0.00 ± 0.01	NS
CH_4 emissions, g d^{-1} pig^{-1}	Through room exhaust	0.41 ± 0.72	0.68 ± 0.78	***	2.77 ± 1.87	2.10 ± 2.18	***
	Through pit exhaust	0.83 ± 0.63	0.96 ± 0.50	***	2.05 ± 1.36	2.41 ± 1.60	***
	Total	1.15 ± 0.77	1.55 ± 0.98	**	4.79 ± 3.17	4.47 ± 3.03	NS
CO_2 emissions, g d^{-1} pig^{-1}	Through room exhaust	1233 ± 315	1437 ± 383	***	1268 ± 609	1044 ± 459	***
	Through pit exhaust	367 ± 174	488 ± 211	***	562 ± 154	773 ± 233	***
	Total	1588 ± 442	1903 ± 517	***	1814 ± 703	1814 ± 636	NS

Sig.: significance; NS: not significant;
* p<0.05;
** p<0.01;
*** p<0.01.

Most CO_2 emitted from room exhausts (Table 5.5). In summer, CO_2 production from system-W on average was 19.8 % higher than that from system-C. In winter, CO_2 productions from both system-C and system-W were the same. CO_2 production increased throughout all the fattening periods (Fig. 5.4).

5.4. Discussions

5.4.1. Gas release

In livestock building, NH_3 emissions were principally generated from the microbial degradation of urea by the enzyme urease in faeces (Muck & Steenhuis, 1981). The NH_3 release process is closely related to air velocity at the manure surface, area of manure surface, air and manure temperatures, pH change in the surface manure, the manure production by animals, and etc. (J. Ni, 1999). In the current study, factors that may influence NH_3 emissions were similar in system-C and system-W except air velocities.

Varied NH_3 emission rates for fattening pigs in conventional mechanically ventilated fattening pig facilities with slatted floor have been reported in literatures. Groot Koerkamp et al. (1998) presented values of 4.44, 9.24, 7.67 and 7.39 g NH_3 d^{-1} pig^{-1} for England, the Netherlands, Denmark and Germany, respectively. Philippe, Laitat, Canart, Vandenheede, and Nicks (2007) observed a mean NH_3 emission rate of 6.22 g d^{-1} pig^{-1} during fattening period. Ngwabie, Jeppsson, Gustafsson, and Nimmermark (2011) obtained values of 4.56-4.80 g NH_3 d^{-1} pig^{-1} for fattening pigs in three batches. With fattening pigs kept under PPV system, average emissions of 4.67 and 6.55 g NH_3 d^{-1} pig^{-1} were measured from system-C and system-W, respectively, during summer. The comparable values for winter period were 4.57 and 4.59 g NH_3 d^{-1} pig^{-1} from system-C and system-W, respectively.

N_2O is produced during incomplete nitrification and denitrification processes which need both aerobic and anaerobic conditions (Monteny, Bannink & Chadwick, 2006). Neither of the two conditions occurred in the slurry under the slatted floor (Cabaraux et al., 2009). This could be the reason why very low N_2O emissions were observed in current experiments. However, Cabaraux et al. (2009) pointed out that N_2O emissions from manure on the floor could occur in pig houses with slatted floor. In this study, the pit ventilation under slatted floor induced probability of air flow near the floor which was likely to eliminate the N_2O emission from floor as creating limited anaerobic conditions. Since there was almost no N_2O emission in this experiment, the influence factors regarding N_2O release won’t be considered in the following parts.

CH_4 originates from enteric fermentation by pigs and anaerobic degradation of organic matter in manure (Cabaraux et al., 2009; Hellmann, Zelles, Palojärvi & Bai, 1997). The production of enteric CH_4 is related to the fermentative capacity of hindgut and the level of dietary fibre (Philippe et al., 2008). The production of manure CH_4 is under anaerobic conditions and promoted by high temperature (Amon, Kryvoruchko, Amon & Zechmeister-Boltenstern, 2006; Sommer & Møller, 2000). Besides, straw supply as rooting material was believed for inhibiting CH_4 production because of greater manure aeration (Amon et al., 2006; Philippe, Laitat, Nicks & Cabaraux, 2012).

In this study, average CH_4 emissions were 1.15 and 1.55 g d^{-1} pig^{-1} for system-C and system-W, respectively, during summer. The values for winter period were 4.79 and 4.47 g CH_4 d^{-1} pig^{-1} from system-C and system-W, respectively. There were two sharp decrease of CH_4 emission during the slurry emptying processes (Fig. 5.4).

Normally, there are two main source of CO_2 production in a piggery without combustible heating: animal respiration and manure release (J. Q. Ni, Hendriks, Coenegrachts & Vinckier, 1999; Zong, Zhang, Feng & Ni, 2014). CO_2-exhalation by pigs is function of energy metabolism rate, which is related to body mass, feeding level and nutrient composition of the diet, and animal activity (CIGR, 2002; Pedersen et al., 2008). CO_2-release from manure comes from (1) hydrolysis and catalysis of animal urea by enzyme urease and (2) anaerobic digestion of organic components in manure (J. Q. Ni, Vinckier, Hendriks & Coenegrachts, 1999).

Some studies concluded the quantity of CO_2 released from manure was very small compared to CO_2 exhaled by pigs' respiration (CIGR, 1992; Feddes & DeShazer, 1988). On the other hand, some studies stated the quantity of CO_2 from manure release had considerable contribution to the total CO_2 production (J. Q. Ni, Hendriks, et al., 1999; J. Q. Ni, Vinckier, et al., 1999; Pedersen et al., 2008). Pedersen et al. (2008) stated that the CO_2 produced from manure release varied between houses with different control and management systems. In the current experiment, the quantity of CO_2 released from manure contributed 2.3-3.4% of the total CO_2 production, which was described in a pilot study by (Zong, Zhang, et al., 2014).

5.4.2. Influence of different types of air inlets

The ventilation system of animal houses has significant influence on local thermal conditions and gaseous release (Barber & Ogilvie, 1982; Zhang et al., 1996). Meanwhile, the dispersion and deposition of gaseous contaminants are mostly affected by airflow inside the livestock building (Zhang & Strom, 1999).

In current study, the two different designed air inlets induced two different ways of air supply into rooms and consequently, two kinds of airflow conditions. In system-C, supply air had to go through the attic space and insulated diffusion ceiling, which could be warmed up on the path. In contrast, for system-W, supply air was into the room from outdoor directly. As a result, the incoming air was a little warmer in system-C than in system-W. To maintain a same setting indoor air temperature, more outdoor air was required for system-C than for system-W (Table 5.3). Higher ventilation rate could result in lower ammonia concentrations due to air dilution. The impacts of air dilution was obviously observed in the gas concentrations in summer condition when ventilation rate was on average 15.76 m^3 h^{-1} pig^{-1} higher in system-C than in system-W. However, in winter condition, since the average room ventilation rate in system-C was only 3.15 m^3 h^{-1} pig^{-1} higher than that in system-W (Table 5.3), the effect of air dilution on gas concentrations was not clear. The gas concentrations were always higher in room air and lower in pit air from system-C than from system-W (Table 5.4).

Despite gas dilution, gas concentration is principally determined by gas release which is affected by airflow patterns and air exchange rates between room and pit spaces (Ye, Saha, et al., 2009; Ye, Zhang, et al., 2009). In system-W, the injected air *via* wall-jet formed a full return flow in the room (Fig. 5.2), which generated higher air speed and turbulence near the slatted floor comparing to system-C (Bjerg, Zhang & Kai, 2008, 2011). The downward air at one end of the pens could easily penetrate the pit headspace through the openings of slatted floor. In summer, a part of plunged air could get out from pit to room space, which resulted in high air exchange between room and pit air (Morsing, Strom, Zhang & Kai, 2008; Zhang et al., 2008). Mass transportation was driven in the exchange air as well. The rest of air joined the air flow in the pit headspace and exited from the pit exhausts installed on the side-wall. However during winter, the inlet airflow momentum was comparably weaker and the plunged air in system-W primarily exited from the pit exhausts as the return flow at the side-wall under lying area, which increased gas removing via pit exhausts. Since no much pit air from pit returned to the room space, gas emission through room exhaust was relatively low. The total emissions were similar between the two systems during winter.

Both PPV systems had short circuiting of incoming air because of no perfect mixing. The short circuiting of incoming air could dilute the ammonia concentration in room exhaust, and made the concentration value lower in room exhaust air than in AOZ. It had no influence on ammonia emissions from the pig room since emission subjected to the mass conservation.

More detailed discussion of the effects of air inlets on ammonia emission and concentration can be found in a pilot study of (Zong, Feng, et al., 2014).

5.4.3. Seasonal influence

Room ventilation requirement increased as outdoor temperature was high (Fig. 5.2). Therefore, larger amount of fresh air was required in summer than in winter (Table 5.3), which resulted in bigger inlet air momentum (mass × velocity) in summer than in winter. Since the size of the opening of wall inlet would reduce to creating high speed supply air, the difference of inlet air momentum between summer and winter was even significant for system-W. The higher inlet air momentum was likely to increase air exchange rate between room and pit space and also increase air speed on the slurry surface. Higher mass transportation including NH_3 and GHG was driven in the exchange air.

In summer, the outside temperature was close to and even higher than the indoor temperature which made indoor temperature approach to the higher threshold of the P-band controlled temperature. However in winter, the outside temperature was much lower than the indoor temperature and the indoor temperature was likely to be close the lower threshold of the P-band controlled temperature. As a result, the mean indoor temperature was relatively lower in winter than in summer despite the same setting indoor temperature (Table 5.3).

The variation of outdoor temperatures under different seasons and consequently the ventilation rates and indoor climate characteristics influenced the results of the gaseous release. In addition, the different indoor thermal conditions under summer and winter influenced the behaviours of pigs which further affected gas volatilization (Saha et al., 2010).

In general, the gas concentrations in exhaust air were higher in winter than in summer due to lower air dilution rate (Table 5.4). The only exception was NH_3 concentrations in pit exhausts which had a little bit lower values in winter.

The mean gas emissions were also lower in winter than in summer. This is agree with previous study which concluded that higher ventilation rate induce higher gaseous emissions (Aarnink & Wagemans, 1997; Arogo, Zhang, Riskowski, Christianson & Day, 1999; Saha et al., 2010; Ye, Zhang, Li, Strøm & Dahl, 2008; Zhang et al., 2008).

The fattening period in different seasons had a significant influence on CH_4 emissions. Differences were mainly caused by the course of the outside temperature during the fattening period. Higher emissions were found in the fattening period in summer than in winter.

Based on the mechanism of NH_3 production and the variance of all influencing factors, the air velocity above the manure surface mainly influenced the NH_3 emission rate in this study. During summer there was more air flow and higher air speed above the emitting surface, which caused more NH_3 volatilize. Besides, higher temperature could also enhance emissions.

Based on the mechanism of CH_4 production, the dietary fibre content affected the enteric-CH_4 production and anaerobic condition and high temperature could promote manure-CH_4 production. The fibre content in pig diet was a little higher in summer than in winter (Table 5.1), which could result more enteric-CH_4 production. Higher air flow and air speed around slatted floor reduced the possibility of anaerobic conditions for manure-CH_4 production in summer, despite the higher temperature.

Most CO_2 emission was from animal respiration with a very small proportion from manure release in current set-up (Zong, Zhang, et al., 2014). The weight of pigs was believed to be the most important factor for the daily CO_2 production. Besides, CO_2 production is correlated with animal activity (Ngwabie et al., 2011). A theoretical approach for estimating CO_2 production is the respiratory quotient (RQ) defined as the volume of CO_2 produced divided by the volume of O_2 consumed: the higher RQ, the higher CO_2 production (Pedersen et al., 2008). In current study, pigs were raised under almost same conditions except the air inlet of ventilation during the same period. In winter, the CO_2 production (1814 g d^{-1} pig^{-1}) was almost the same for both systems. However in summer, the CO_2 production was much higher from system-W (1903 g d^{-1} pig^{-1}) than from system-C (1588 g d^{-1} pig^{-1}). One explanation could be that those pigs in system-W had higher RQ when large volume of outdoor air was directly supplied to the AOZ. This effect was not obvious for the winter condition with small volume of supplied air under system-W. If we combine the measurement values of both systems, the mean CO_2 production was a little higher in winter (1814 g d^{-1} pig^{-1}) than in summer (1746 g d^{-1} pig^{-1}). It was also revealed in the feed consumptions (Table 5.2), pigs consumed more feed to generate heat during cold season than during warm season.

5.4.4. Advantages of applying PPV system

Indoor air concentration of NH_3 is a key parameter for determining air quality in pig house due to its significant impact on the health of both human beings and animals inside the building (Saha et al., 2010; Ye et al., 2008; Zhang et al., 2005). Many literatures have reported indoor air concentration of NH_3 in conventional mechanically ventilated fattening pig facilities with fully slatted floor. Groot Koerkamp et al. (1998) presented average indoor NH_3 values between 12.1 and 18.2 ppm in Northern Europe with 14.9 ppm for Denmark. Saha et al. (2010) obtained an average concentration of 6.5 ppm from measurement at early and middle of the fattening period in a facility with only top-roof ventilation. In current experimental rooms with PPV system, the average indoor NH_3 concentrations were only 2.1-3.4 ppm in summer and 4.2-4.3 ppm in winter, which were much lower than those from fattening pig rooms using conventional mechanical ventilation system. The remarkable improvement in indoor air quality was mainly caused by the negative pressure in the pit headspace with PPV, which could prevent the upward air exchange through the slots, hence lowered ammonia concentrations in the pig rooms (Aarnink & Wagemans, 1997; Gustafsson, 1987). Animal welfare was improved as better indoor quality was achieved in the animal house with PPV system.

Although the PPV only accounted for 10% of the maximum ventilation rate, approximately half of the whole NH_3 emissions were from the pit exhausts. High concentrated air in pit headspace was removed directly by pit ventilation before moving up to room space. The pit exhaust air could be cleaned effectively by using air purification system. Since the volume of purifying air is largely reduced, the investment and operation costs will also be significantly reduced. An air cleaning device with bioscrubber reported by Phillips et al. (1999) could abate 97.6% of ammonia from the exhaust air. With such air scrubber treating only 10% amount of the maximum required ventilation, NH_3 emission reductions of 46.5% and 47.3% were estimated in summer for systems C and W, respectively. The comparable reductions in winter were 51.9% and 62.0% for systems C and W, respectively. Therefore, PPV + air-scrubber system could be an efficient mitigation technique for ammonia emission from pig production.

5.5. Conclusions

Ammonia, nitrous oxide, methane and carbon dioxide concentrations and emissions were measured continuously in a fattening pig house with two types of partial pit ventilation (PPV) systems during summer and winter periods.

Using indoor gaseous concentrations as indicator, a partial pit exhaust with only 10% of the maximum ventilation capacity could significantly improve indoor air quality. Rearing pigs in rooms with PPV thus achieved good animal welfare. On average, the indoor concentrations were maintained 2.1-3.4 ppm (for NH_3), 0.4-0.6 ppm (for CH_4), and 800-966 ppm (for CO_2) in summer; and 4.2-4.3 ppm (for NH_3), 5.0-5.6 ppm (for CH_4), and 1491-1542 ppm (for CO_2) in winter. There were almost no N_2O releases in current set-up with slatted floor and pit ventilation under the floor.

Approximately half of the whole NH_3 emission (47-63%) was extracted from pit exhausts. The air purification system for mitigating pollutants from pig house became practical as only treating10% of the exhausted air. The PPV plus air purification system can be an efficient mitigation technique for reducing gaseous pollution from pig production.

Gas emissions of fattening period were mainly influenced by the different air-inlets and seasonal times. The two types of PPV systems (system-C and system-W) resulted in two different kinds of airflow characteristics, which further affected the gaseous release process. More fresh air was required for system-C than for system-W to keep a same setting indoor temperature. Lower gases concentrations were observed in system-C than in system-W during summer. During winter, gases concentrations were higher in room air and lower in pit air from system-C than from system-W. Due to smaller air dilution rate, the gas concentrations in room air were higher during winter than during summer. The daily mean NH_3 emissions were lower, while the daily mean CH_4 and CO_2 emissions were higher, in winter than in summer.

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Chapter 6

Assessment of RANS turbulence models to predict airflow and dispersion in an experimental chamber of pig house with partial pit ventilation system

Paper V:

Zong, C., Zhang, G., 2014. **Assessment of RANS turbulence models to predict airflow and dispersion in an experimental chamber of pig house with partial pit ventilation system**. *Prepared submitting to a peer review journal*.

Abstract

Intensive pig production is a main source of pollution. A partial pit ventilation (PPV) has been developed and proved success on improving indoor air quality and efficiently reduce emission if combined with air purification system. In this paper, we aim to evaluate the performance of five widely used turbulence models, the standard k-ε (SKE), the renormalization group k-ε model (RNG), the realizable k-ε model (RKE), the standard k-ω model (SKW) and the shear stress transport k-ω model (SST-KW) on predicting airflow velocities and concentrations in a full scale climate chamber of pig house with a PPV system. The turbulence models were evaluated by comparing the numerical results with experimental data. Results show that the overall air velocities both on horizontal and vertical directions and concentration profile along the length of chamber can be revealed by numerical results. The RNG k-ε was found to be the best in predicting airflow and dispersion in a pig model with PPV system among the five investigated RANS turbulence models.

Keywords: *pig production, partial pit ventilation system, RANS turbulence models*

6.1. Introduction

Intensive pig farms are usually confined and popular in Denmark. Nevertheless, these farms are under great pressure due to environmental issues caused by pig production. The airborne pollutants emitted from pig buildings can lead to poor indoor air quality and cause negative impact to neighbouring atmosphere and aquatic environment.

In confined pig buildings, ventilation is the primary approach used to control the indoor climate. The release and transport of airborne pollutants was highly affected by air motion inside the building (Morsing, Strom, Zhang & Kai, 2008). Thus, effective and practical methods to control the airflow for reduction of gaseous emissions from pig buildings are highly required. In order to improve the control efficiency, a partial pit ventilation (PPV) system which applying an extra pit exhaust near the pollutants source zone has recently been developed. High concentrated airborne pollutants from slurry pit can be extracted directly *via* pit air exhaust before moving up to the room space through slatted floor openings (Zong, Feng, Zhang & Hansen, 2014).

Information on the airflow characteristics and contaminants distribution in pig house is useful for understanding the fundamental knowledge for further application. However, detailed measurements both in laboratory and field conditions are very expensive and often difficult. As an alternative approach, Computational Fluid Dynamics (CFD) is a useful and reliable tool to predict airflow and dispersion across wide research areas. Most CFD models have been successfully used for simulating airflow and dispersion inside confined spaces (Lee et al., 2013; Norton, Sun, Grant, Fallon & Dodd, 2007). However, CFD need to be evaluated before it can be used as a practical engineering tool for predictions in buildings. The selection of a turbulence model greatly influences the prediction accuracy of airflow and dispersion in buildings because it strongly affects the reproduction of the flow structure in buildings (Liu, Niu & Kwok, 2013). Various turbulence models have been applied to develop understanding and proper modelling techniques for the flow and dispersion in buildings. Steady RANS (Reynolds-average Navier-Stokes) model is the most widely used approach for airflow and dispersion modelling in many applied researches referring to actual buildings.

Up until now, very few studies on modelling slatted floor in agricultural buildings are available in the literature. Due to the involvement of slatted floor and pit exhaust, the flow becomes complicated. CFD simulation has been performed to evaluate the efficiency of a partial pit ventilation system to reduce ammonia emission in pig units with animals and slatted floor. In the work of (Bjerg, Zhang & Kai, 2008a, 2008b), the slatted floor was modelled as porous media. However, this work lacked of validation with measurements and the simplification of modelling slatted floor needs assessment. Wu, Zhang, Bjerg, and Nielsen (2012) applied different RANS models to assess a partial pit ventilation system to reduce emission under slatted floor in a 1:2 pit model of a cattle building in which the slatted floor was simulated in geometrical details. RMS (Reynolds Stress Models) was found to be the most suitable turbulence model to predict the removal capability of a PPV system to reduce emission under slatted floor.

This study focuses on the comparison of results from the climate chamber of pig building model and the corresponding CFD predictions. The objective is to evaluate the performance of steady RANS turbulence models on the airflow and dispersion predictions in a climate chamber of pig building with a partial pit ventilation system through comparison.

6.2. Materials and methods

6.2.1. Experiment set up

6.2.1.1. Ventilation chamber of pig house

An experimental ventilation chamber with inside dimensions of 4.47 m × 1.17 m × 2.89 m ($L \times W \times H$) was built as a sub-section of a fattening pig house which corresponded to a full scale pig pen with half width (Fig. 6.1). The front panel of the chamber was made of transparent glass, and the back and side panels were made of plywood which were painted in dark color for facilitating velocity measurements and visualization of airflow patterns with illuminated smoke (Fig. 6.1). The chamber was divided into two spaces by floor. The room space was above the floor with a height of 2.375m. The pit headspace under the floor was 0.515 m in height. Fully slatted floor was a traditional type floor commonly applied in Danish pig production, which was equipped in the chamber in this study. The slatted floor had a thickness of 0.078 m and the opening ratio of floor was 0.19.

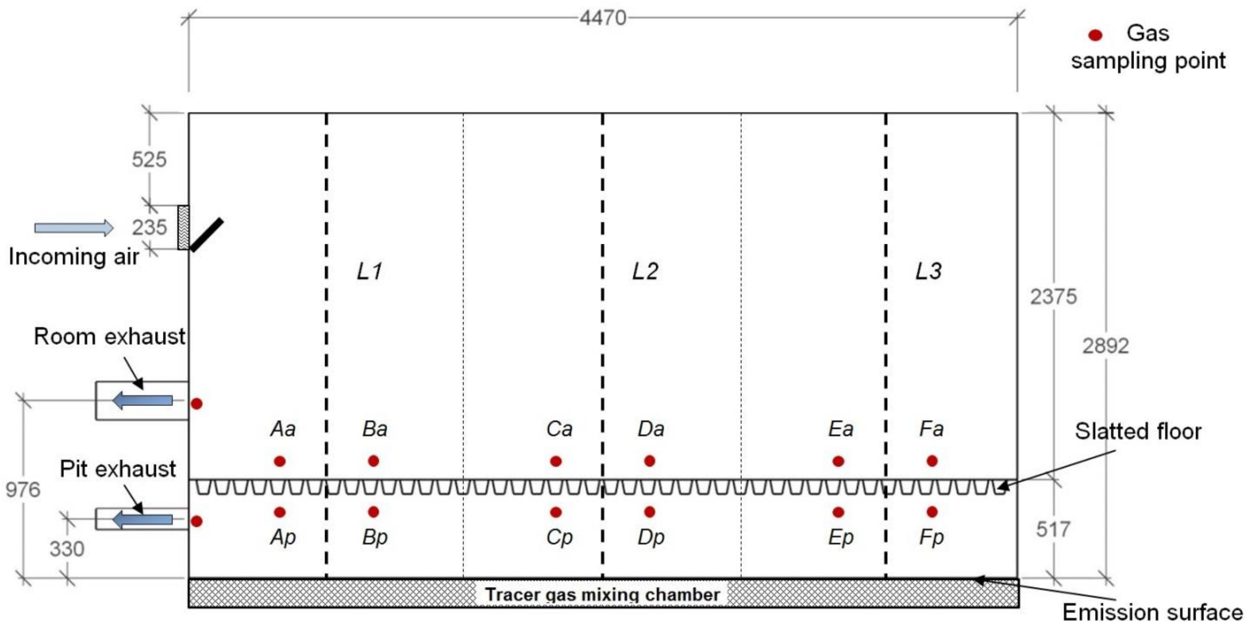

Fig. 6.1. - The schematic diagram of experimental chamber and sampling positions, all dimensions are in mm.

6.2.1.2. Ventilation systems

The experimental chamber was equipped with a negative pressure ventilation system, which was commonly applied in pig production housing in Denmark. Ventilation inside the chamber was driven by a partial pit exhaust and a sidewall room exhaust (Fig. 6.1). Room exhaust was a sealed iron pipe outlet with a diameter of 200 mm installed on the left sidewall, which was the major air outlet. The pipe was connected *via* a flexible duct to a channel fan (Lindab type VBU 200B, Denmark) discharging the air to outside. Pit air was extracted by another type of fan (Lindab type VBU 100B, Denmark) *via* a 110 mm-diameter pipe outlet installed in the left wall just beneath the floor. Fresh air was injected into the chamber via wall jet air inlet (Fig. 6.1). The wall jets were placed 1.62 m above the floor, and in the symmetrical plan of the pig pen. The opening of wall jet air inlet was regulated by changing the adjustable 6.flap. To ensure the inlet air speed strong enough to reach the animal occupied zone (AOZ), the pressure difference (ΔP) between inside and outside of the chamber is kept approximately at 10 Pa. The angle for the flap to the horizontal plain was kept at 45 degree in the experiment. The designed capacity of ventilation rate ($\mathrm{VR_c}$) was 800 m^3 h^{-1}. The pit ventilation rate ($\mathrm{VR_p}$) was set as 10% of $\mathrm{VR_c}$, while the room ventilation rate ($\mathrm{VR_r}$) was set at 50% of the $\mathrm{VR_c}$ during the experiment.

6.2.1.3. Measurements

Measurements were carried out under isothermal conditions (Fig. 6.1). Table 6.1 demonstrates the airflow characteristics and settings for air inlets.

Lindab FMU/FMDRU 200-160 and FMU/FMDRU 100-80 flow meters (Denmark) was used to measure the room and pit ventilation airflow rate, respectively. The accuracy of the flow measuring method is 5-10% depending on the distance to the flow disturbance. The ventilation flows in the duct was determined using the equations:

$$VR_r = 105.84\sqrt{\Delta Po} \quad (1)$$

$$VR_p = 26.35\sqrt{\Delta Po} \quad (2)$$

where *VR* is ventilation rate, m^3 h^{-1}; *ΔPo* is pressure difference between upstream and downstream side of the orifice, Pa. The pressure differences were measured using a TSI pressure probe (Model 9596, TSI, USA) with an accuracy of ±0.7%.

A two-dimensional Laser Doppler Anemometer (LDA) (DANTEC, Skovlunde, Denmark) was used to measure air velocity at the sampling positions along three sampling lines L1:L3 (Fig. 6.1), which were in a plane 280 mm to the front glass wall. Each point was measured 10 min.

Airflow patterns were observed using smoke from a smoke machine (Z-series II, Antari Ltd., Taiwan) and a laser sheet, which could provide a visualization of the path of airstreams.

N_2O was used as a tracer gas in this study. A constant N_2O flux of 100 ml min^{-1} was supplied uniformly into a mixing chamber below the pit space, and emitted through a wooden plate with 150 holes with diameter of 5-mm and two-layer diffusion floor surface into the pit space under the floor (Fig. 6.1). Four reference sampling points in the mixing chamber along the length of chamber were used to monitor the uniformity of N_2O concentration in the mixing chamber. The N_2O concentration was measured by INNOVA multi-gas Monitor (type 1312, Denmark) and a multiplexer (type 1309, Denmark). The sampling locations are points A:F in the animal occupied zone (AOZ) 200 mm above the floor surface and in the pit headspace 278 mm under the floor surface (Fig. 6.1). The sampling period for each N_2O measurement was 40 s, followed by 20 s flushing time to replace the air in the measuring chamber of the Monitor before a new measurement started.

Table 6.1 - Airflow characteristics in the air inlet of the climate chamber.

Total ventilation rate, $m^3\ h^{-1}$	VR_r/VR_c [a], %	ACH [b]	Wall-jet inlet			
			Inlet air velocity, $m\ s^{-1}$	Inlet Re	J [c]	ΔP, Pa
480	50	31.9	2.83	27177	0.0026	9.5

[a] VR_r/VR_c is the ratio of room ventilation rate to the designed capacity of ventilation rate, which is 800 $m^3\ h^{-1}$ in this study.
[b] Air exchange rate.
[c] Jet momentum number as proposed by Barber and Ogilvie (1982).

6.2.2. Computational modelling

6.2.2.1. Geometry and grid convergence

In the simulation, the size of the geometry was based on the dimension of the experimental chamber, as shown in Fig. 6.1. The envelope of the chamber was specified without thickness. X, Y, Z coordinates was aligned with the length, height and width of the chamber, respectively.

The computational domain was discredited by structured hexahedral cells for this case. Grid independence was analysed by using high density grids (total elements: 2 930 138; total nodes: 2 803 260), normal density grids (total elements: 1 261 689; total nodes: 1 190 952) and low density grids (total elements: 590 188; total nodes: 550 960).

As for the normal grid, the size of the control volumes placed close to the walls and wall jet openings was 0.01 m and close to the floor slot openings was 0.006 m. The stretching factor of 1.1 of each edge of the geometry was adapted.

6.2.2.2. Turbulence models and numerical methods

Commercial CFD software Fluent 15.0 (ANSYS Inc., US) was used for the calculations based on finite volume method.

Standard k-ε (SKE), renormalization group k-ε (RNG), realizable k-ε (RKE), standard k-ω (SKW) and shear stress transport k-ω (SST-KW) turbulence models were selected in this work. The performance of predicting airflow and dispersion on the basis of these turbulence models were assessed. More information about the turbulence models can be found in the related references. The model constants used in this study are listed in Table 6.2.

The second order upwind spatial discretization scheme was employed for momentum, turbulent kinetic energy and turbulent dissipation rate. Standard and SIMPLE methods were employed for pressure and pressure-velocity coupling, respectively.

Table 6.2 - Model constants for the turbulence modes.

Model	Model constants *	
SKE	$C_{1\varepsilon} = 1.44$; $C_{\mu} = 0.09$;	$C_{2\varepsilon} = 1.92$; $\sigma_k = 1.0$; $\sigma_\varepsilon = 1.3$
RNG	$C_{1\varepsilon} = 1.42$;	$C_{2\varepsilon} = 1.68$
RKE	$C_{1\varepsilon} = 1.44$; $\sigma_k = 1.0$;	$C_{2\varepsilon} = 1.9$ $\sigma_\varepsilon = 1.2$
SKW	$\sigma_k = 2.0$;	$\sigma_\omega = 2.0$
KWSST	$\sigma_{k,1} = 1.176$; $\sigma_{\omega,1} = 2.0$;	$\sigma_{k,2} = 1.0$; $\sigma_{\omega,1} = 1.168$

* ANSYS (2013)

6.2.2.3. Dispersion modelling

Nitrous oxide (N_2O) was chosen as the pollutant same with the experiment. The convection-diffusion approach was used for the pollutant dispersion which was simulated by the scalar transport equation. The transport equation for N_2O is written as (Baik & Kim, 1999):

$$\frac{\partial \overline{C}}{\partial t} = \nabla \cdot \left(D_m \nabla c\right) - \nabla \cdot \left(\overline{v} \cdot \overline{C}\right) + S_c \tag{3}$$

where $\overline{C}$ is the mean concentration of a passive pollutant, t is the time, $\overline{v}$ is the mean velocity, D_m is the mass diffusivity for the scalar variable, S_c denotes the source or sink term of the pollutant, which was set as constant species mass fraction of NH_3 in the simulations, ∇ represents gradient and $\nabla \cdot$ represents divergence.

6.2.2.4. Boundary conditions

The boundary conditions considered in this study are shown in Fig. 6.2. In order to obtain better agreement between experimental and numerical results, boundary conditions adopted in current simulations were almost the same as those in the experimental ventilation chamber.

Since the chamber was driven by the two exhaust fans on the sidewall (Fig. 6.1), the real exhaust openings were treated as velocity inlets in the simulation. The measured room and pit ventilation rates via exhausts were converted to velocities and were used as the input values for the velocity inlets, which were facing opposite with x-direction. On the other hand, the real inlet of the chamber was defined as pressure outlet. The bottom surface of the pit headspace was specified as non-slip wall and appointed as an emission surface. The tracer gas was treated as a scalar quantity in the simulation and 1 kg s^{-1} m^{-2} was set as the scalar generation rate on the emission surface. No scalar distribution was assumed to the whole domain as initial condition. Other surfaces were considered as non-slip walls.

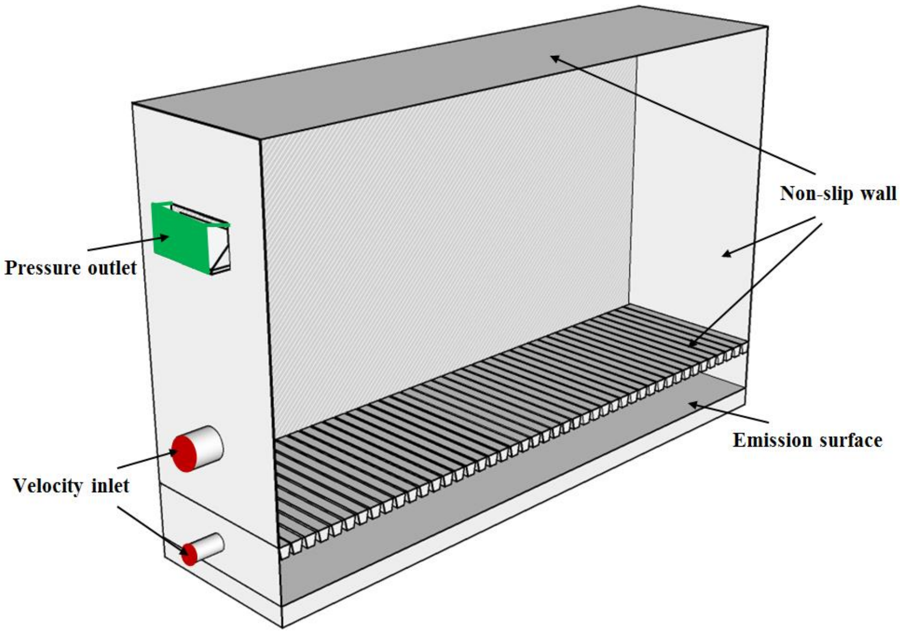

Fig. 6.2 - Layout of computational domain and boundary conditions.

6.3. Results and discussion

6.3.1. Velocity profiles

The two-dimensional velocity vectors were measured on the three parallel lines (L1:L3) in the chamber (Fig. 6.1) following corresponding simulations afterwards. Fig. 6.3 shows the horizontal and vertical air velocities at different heights on the three lines in the chamber obtained by experimental measurements and those calculated using different RANS turbulence models.

In the experimental measurements, the variation trend of horizontal velocities along the three lines was generally similar with high speed airflow moving right near the top-ceiling and relatively low speed return flow to left near floor region (Fig. 6.3). This feature for horizontal air velocity was typical for a pig room with sidewall jet inlet (Zhang & Strom, 1999). Before reaching AOZ, the supplied air was mixed and warmed up with upper room air. The horizontal velocities in the pit headspace under floor were much lower compared with those in the room space above the floor, and they moved towards right direction along all the three measured lines. Vertical velocities were upward along L1 and L2 and downward along L3. It also means that air entered the pit space from right side of chamber, and exited the pit from middle and left part of the floor. This is consistent with previous study regarding side-wall ventilation in pig housing (Ye et al., 2009).

Through the comparisons between experimental and simulation results, it can be seen that the overall velocity profiles both on horizontal and vertical directions were revealed by numerical results (Fig. 6.3). On the line L1, the predicted results are generally acceptable in comparison with experimental data. However, in the upper part of the chamber, both the horizontal and vertical velocity values were overestimated by all the RANS simulations compared with the experimental data. On the line L3, the discrepancies of vertical velocity values between simulation and measurement were relatively larger in comparison with those on other lines. The SST-KW model was in better agreement with the measurements, while noticeable discrepancies still exist in some particular regions.

The quantified discrepancies between the simulated and the measured values were analysed using relative prediction errors defined in Eq. (4):

$$Error = abs\left(\frac{v_m - v_s}{v_m}\right) \quad (4)$$

where v_m and v_s represent measured and simulated values, respectively.

Table 6.3 lists the relative error values between simulated and measured results at different measurement locations on line L1, L2 and L3, respectively. For horizontal velocity values, better agreements between experimental measurements and simulations using all the investigated turbulence models were observed on L2, while relatively larger discrepancies occurred on L1 (Table 6.3a). The turbulence models of RNG and SKW predicted horizontal velocities in closer agreement with the experimental results compared with other turbulence models. On the other hand for vertical velocity values, better agreements between experimental measurements and simulations using all the investigated turbulence models were observed on L1 and L3, while relatively larger discrepancies occurred on L2 (Table 6.3b). The turbulence models of RNG overall predicted vertical velocities in best agreement with the experimental results among all turbulence models.

6.3.2. Concentration profiles

The mean concentrations of N_2O were measured at six sampling locations (A:F) both above and below the slatted floor (Fig. 6.1) and were calculated using different turbulence models in CFD.

Experimental measurements showed that higher N_2O concentrations were observed in the pit headspace than in room air (Fig. 6.4). The N_2O concentration levels along the floor length both above and under the slatted floor decrease with the distance from the left sidewall. Much higher concentrations were at location A and B near the left sidewall than other measuring locations.

The predicted normalized concentration profiles along the length of chamber were compared with measurement results (Fig. 6.4). Two cases were selected for comparisons, with the concentration profiles in the AOZ above the floor and in the pit headspace under the floor. In general, the basic concentration features were revealed by the simulation results. In the AOZ, all the prediction results of the concentration at location C to F showed acceptable agreement with the experimental data, while large discrepancies between prediction and measured results were found at location A and B. In the pit headspace, all the prediction results were underestimated the concentration at location A and B compared with experiments.

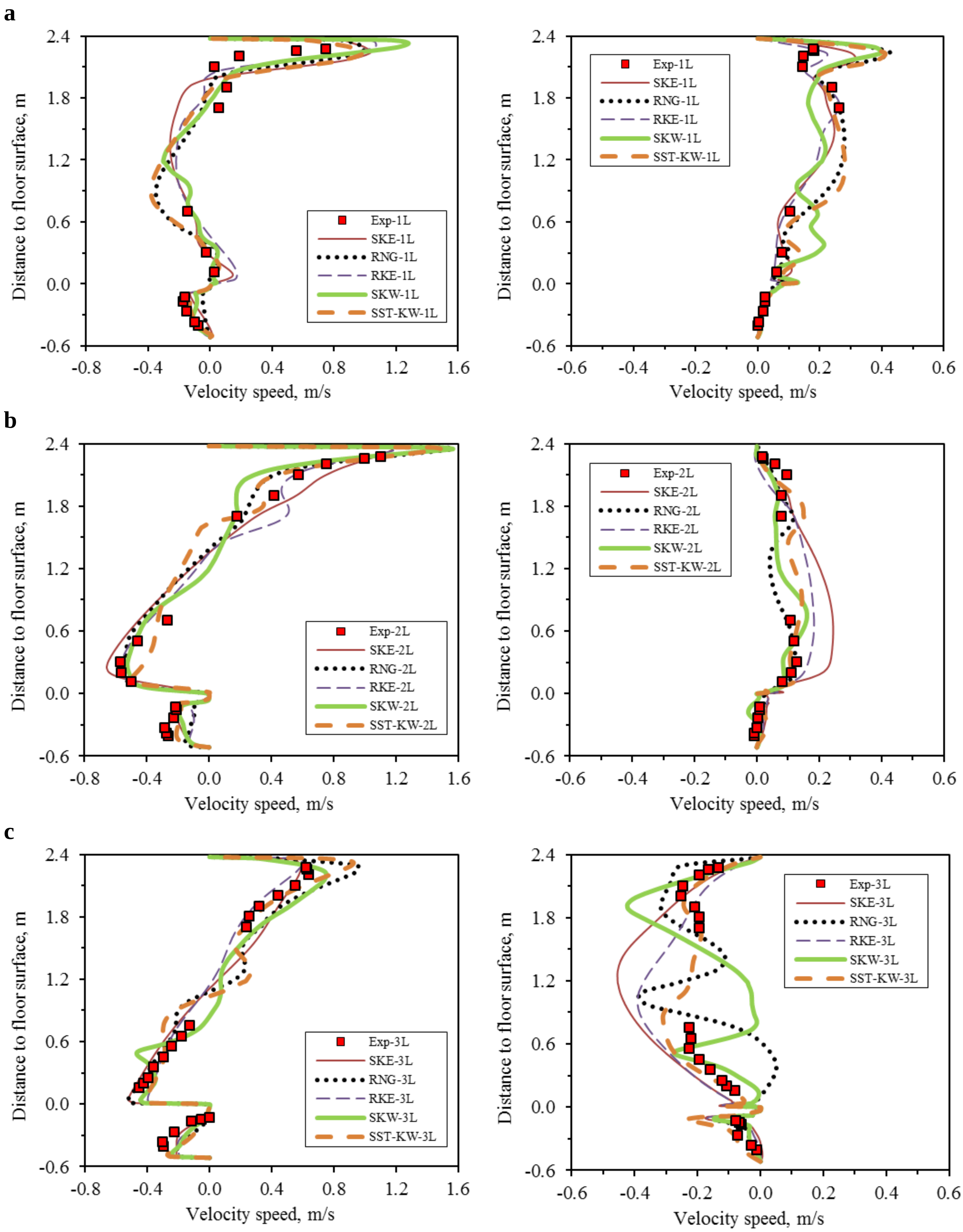

Fig. 6. 3 - Comparison of horizontal (left) and vertical (right) velocities profiles between CFD results and experimental measurements along three measuring lines: (a) L1; (b) L2; and (c) L3.

Table 6.3a - Relative prediction errors of U between numerical results with experimental measurements

	SKE-U			RNG-U			RKE-U			SKW-U			SSTKW-U		
Y-real	L1	L2	L3	L1	L2	L3	L1	L2	L3	L1	L2	L3	L1	L2	L3
Above floor															
2.27	0.348	0.04	0.061	0.317	0.011	0.521	0.344	0.101	0.072	0.47	0.095	0.077	0.251	0.004	0.411
2.25	0.82	0.02	0.076	0.744	0.034	0.498	0.695	0.079	0.101	0.779	0.133	0.123	0.721	0.001	0.345
2.20	4.027	0.215	0.108	3.467	0.05	0.395	2.79	0.012	0.172	2.827	0.196	0.155	3.858	0.015	0.199
2.10	16.091	0.309	0.041	10.957	0.25	0.318	5.639	0.031	0.2	8.05	0.47	0.251	15.934	0.215	0.089
1.90	2.292	0.32	0.362	1.04	0.329	0.402	1.338	0.121	0.119	0.446	0.583	0.58	0.848	0.218	0.105
1.70	4.55	0.653	0.505	1.842	0.231	0.366	2.63	1.686	0.228	1.529	0.07	0.314	2.553	0.061	0.046
0.70	0.203	0.732	0.777	1.117	0.658	0.753	0.203	0.482	0.624	0.172	0.55	0.582	1.148	0.253	1.388
0.50	0.021	0.243	0.341	0.659	0.145	0.224	0.765	0.095	0.158	0.224	0.056	0.548	0.505	0.224	0.21
0.30	0.019	0.145	0.148	2.907	0.047	0.067	4.865	0.006	0.077	3.061	0.077	0.061	0.947	0.273	0.126
0.20	19.85	0.13	0.115	11.598	0.027	0.069	44.083	0.013	0.135	5.963	0.087	0.157	15.902	0.165	0.139
0.11	4.124	0.134	0.083	0.256	0.038	0.05	5.319	0.039	0.164	0.171	0.01	0.154	0.185	0.03	0.158
Under floor															
-0.13	0.25	0.135	14.86	0.705	0.563	3.841	0.016	0.43	11.583	0.469	0.114	18.204	0.226	0.141	10.597
-0.17	0.369	0.087	0.402	0.725	0.58	0.769	0.084	0.486	0.547	0.508	0.077	0.549	0.254	0.136	0.734
-0.27	0.544	0.192	0.177	0.745	0.543	0.559	0.083	0.601	0.366	0.307	0.296	0.381	0.151	0.216	0.58
-0.37	0.763	0.386	0.289	0.703	0.528	0.432	0.035	0.584	0.32	0.156	0.432	0.398	0.102	0.234	0.447
-0.41	0.889	0.413	0.275	0.661	0.46	0.326	0.18	0.53	0.298	0.334	0.445	0.313	0.066	0.2	0.291
Means															
Of each line	3.447	0.260	1.164	2.403	0.281	0.599	4.317	0.331	0.948	1.592	0.231	1.428	2.728	0.149	0.992
Of all points	1.624			1.094			1.865			1.083			1.290		

Table 6.3b - Relative prediction errors of V between numerical results with experimental measurements

	SKE-V			RNG-V			RKE-V			SKW-V			SSTKW-V		
Y-real	L1	L2	L3	L1	L2	L3	L1	L2	L3	L1	L2	L3	L1	L2	L3
Above floor															
2.27	0.406	0.455	0.236	1.134	0.032	0.991	0.016	1.305	0.364	1.115	0.887	0.222	0.986	0.546	0.131
2.25	0.541	0.399	0.295	1.244	0.09	0.647	0.11	1.224	0.411	1.138	0.722	0.217	1.127	0.49	0.217
2.20	1.05	0.634	0.237	1.648	0.44	0.437	0.435	0.995	0.362	1.328	0.685	0.035	1.65	0.679	0.184
2.10	0.711	0.525	0.179	0.755	0.48	0.186	0.165	0.834	0.327	0.577	0.562	0.206	0.925	0.554	0.16
1.90	0.146	0.24	0.373	0.077	0.032	0.527	0.093	0.181	0.044	0.275	0.146	1.04	0.103	0.539	0.17
1.70	0.138	0.509	0.839	0.01	0.475	0.248	0.013	0.52	0.31	0.37	0.264	0.598	0.092	0.907	0.01
0.70	0.281	1.261	0.68	0.442	0.102	0.666	0.136	0.701	0.584	0.797	0.469	0.888	0.526	0.248	0.353
0.50	0.273	1.038	0.391	0.036	0.021	1.109	0.296	0.501	0.331	0.938	0.034	0.13	0.063	0.01	0.246
0.30	0.082	0.811	0.474	0.237	0.064	1.314	0.277	0.27	0.462	1.331	0.351	0.337	0.687	0.174	0.259
0.20	0.49	0.88	0.549	0.122	0.04	1.222	0.207	0.352	0.574	0.427	0.22	0.803	0.715	0.055	0.043
0.11	0.73	0.455	0.772	0.17	0.177	1.155	0.168	0.283	0.801	0.129	0.091	0.914	0.389	0.394	0.076
Under floor															
-0.13	0.067	1.659	0.477	0.255	0.125	0.609	0.049	0.992	0.556	0.172	2.911	0.434	0.295	0.697	1.813
-0.17	0.211	1.928	0.367	0.271	0.195	0.164	0.125	0.98	0.171	0.339	3.602	0.342	0.248	1.036	1.609
-0.27	0.436	6.929	0.875	0.183	0.063	0.467	0.308	5.028	0.707	0.367	1.417	0.495	0.192	8.147	0.129
-0.37	0.196	6.322	1.093	1.225	2.218	0.269	0.329	6.868	0.845	0.986	3.661	0.003	1.339	8.304	1.309
-0.41	0.084	2.896	1.505	2.343	1.425	0.255	0.737	3.376	1.016	2.403	2.125	0.898	2.127	3.359	4.007
Means															
Of each line	0.365	1.684	0.584	0.634	0.374	0.642	0.216	1.526	0.492	0.793	1.134	0.473	0.717	1.634	0.67
Of all points	0.878			0.550			0.745			0.800			1.007		

With regards to different turbulence models, the quantified discrepancies of the concentrations between simulated and measured results were also analysed using relative prediction error calculated by Eq. (4), and summarized in Table 6.4. For concentrations in the AOZ, all the turbulence models got general similar mean prediction errors of approximately 0.5 to 0.7, with the SST-KW predicting concentration values in best agreement with experimental results. For concentrations in the pit headspace, the RNG predicted concentration values in best agreement with experimental results among all the investigated turbulence models.

Table 6.4a - Relative prediction errors of concentrations in the animal occupied zone (AOZ) between numerical results with experimental measurements

Measuring point	SKE	RNG	RKE	SKW	SST-KW
Ap	0.223	0.661	0.252	0.007	0.487
Bp	1.365	1.350	1.116	2.426	0.354
Cp	1.198	0.250	0.998	0.292	0.486
Dp	0.357	0.662	0.461	0.440	0.490
Ep	0.352	0.665	0.436	0.432	0.484
Fp	0.355	0.664	0.438	0.398	0.480
Means	0.641	0.709	0.617	0.666	0.463

Table 6.4b - Relative prediction errors of concentrations in the pit headspace between numerical results with experimental measurements

Measuring point	SKE	RNG	RKE	SKW	SST-KW
Aa	0.204	0.029	0.110	0.124	0.606
Ba	0.363	0.178	0.193	0.023	0.854
Ca	1.300	0.042	0.099	1.421	0.663
Da	1.874	0.271	2.024	2.022	0.863
Ea	0.056	0.454	0.414	0.269	0.905
Fa	1.767	0.323	0.541	3.203	0.466
Means	0.927	0.216	0.563	1.177	0.726

6.3.3. Further discussion

Benefiting from the advantages of CFD techniques, the detailed airflow dispersion routes under different circumstances can be illustrated. As discussed above, regarding airflow and dispersion predictions, the best agreement was achieved by RNG among the five investigated turbulence models. Fig. 6.5 shows the airflow patterns, mean air velocity magnitude and mass fraction of N_2O inside the experimental chamber calculated by RNG turbulence model.

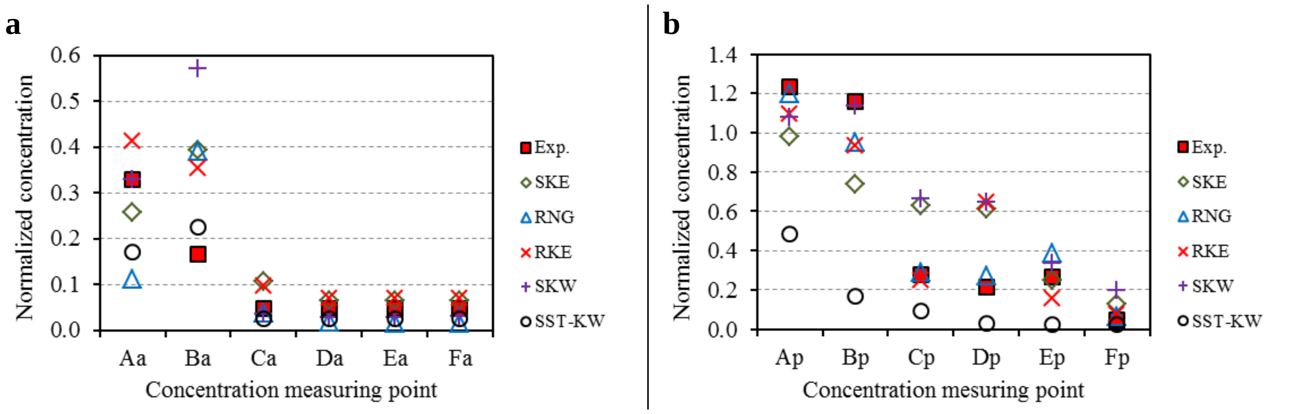

Fig. 6. 4 - Comparison of normalized concentrations between CFD results with different turbulence models and experimental results: (a) in the animal occupied zone above floor and (b) in the pit headspace under the floor.

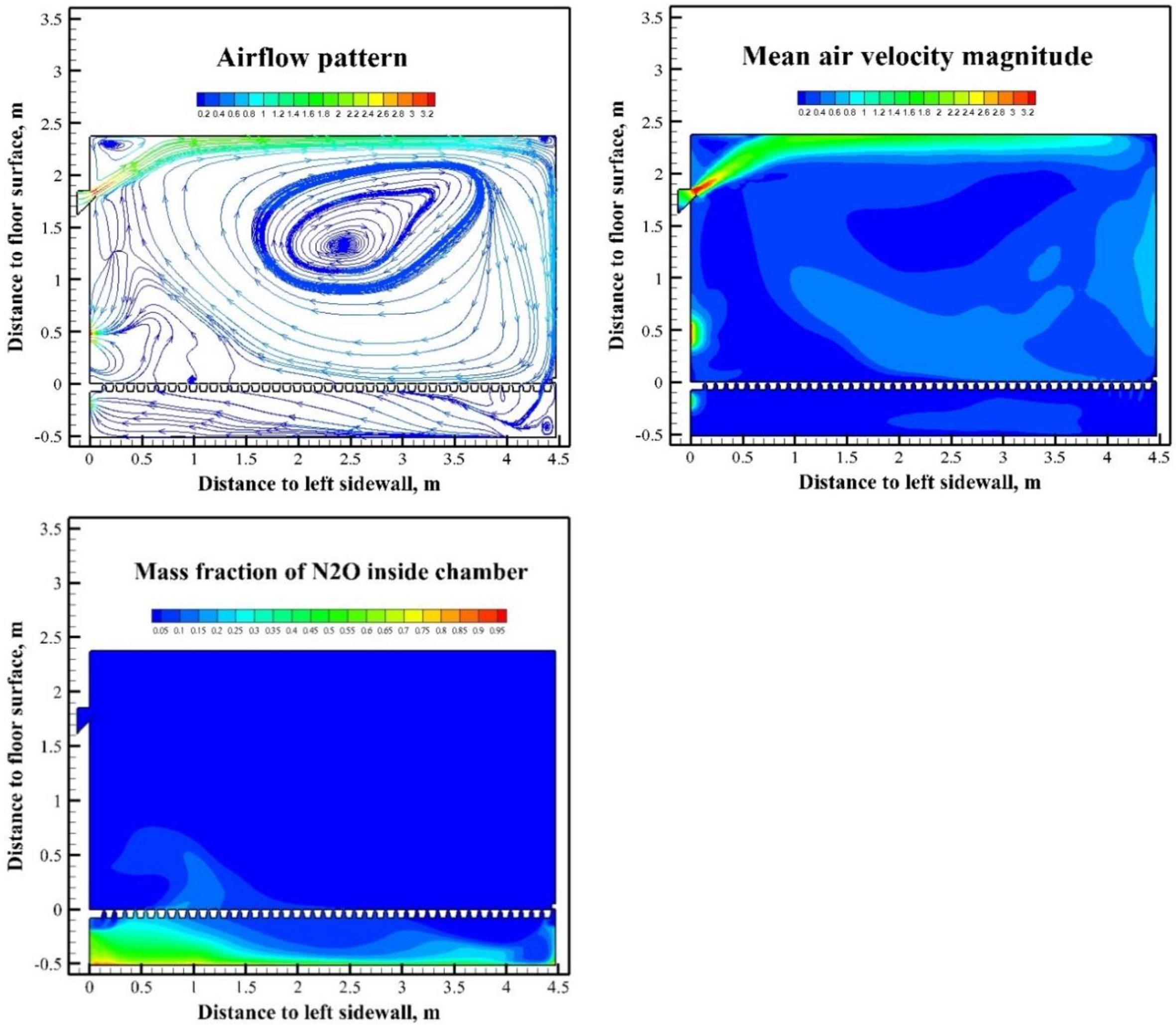

Fig. 6. 5 - Airflow pattern, velocity magnitude and N_2O mass fraction in the experimental chamber predicted by RNG k-ε turbulence model.

As shown in Fig. 6. 5, a big return flow can be seen in the chamber. The supplied air from wall-jet on the left sidewall traveled attaching the top-ceiling and continued down the right sidewall. On reaching the slatted floor, the airflow generally split into two: a primary airflow returning above the floor and another penetrating into the pit headspace below the slatted floor. This phenomenon is consistent with a previous study with only room exhaust unit (Ye et al., 2009). Air with high velocity was observed in the upper part of chamber after injecting through the wall jet inlet. High concentration N_2O was kept under the slatted floor and accumulated on the left side of chamber.

The performance of the numerical approaches has been evaluated by the validation efforts made above, through the comparative exercises provided during this study. As for the target experimental chamber of pig house with a partial pit ventilation system, it requires very fine grid discretization to analyse such flow fields with high precision. Numerical prediction of velocity and N_2O concentration values provided by the RNG k-ε models was reasonably accurate comparing with experimental data. The numerical simulations basically illustrate the airflow and dispersion characteristics.

6.4. Conclusion

In this paper, the performance of the SKE, RNG, RKE, SKW and SST-KW turbulence models was examined for simulating the air velocity and concentration values in an experimental ventilation chamber of pig house with a partial pit ventilation (PPV) system. Through comparisons between experiments and simulations, the overall air velocities both on horizontal and vertical directions and concentration profile along the length of chamber can be revealed by numerical results. Among the five investigated RANS turbulence models the RNG k-ε was found to be the best in predicting airflow and dispersion in a pig model with PPV system.

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Chapter 7

Numerical modelling of airflow and gas dispersion in the pit headspace via slatted floor: Comparison of two modelling approaches

Paper VI:

Zong, C., Zhang, G., 2014. **Numerical modelling of airflow and gas dispersion in the pit headspace via slatted floor: Comparison of two modelling approaches**. *Accepted by Computers and Electronics in Agriculture, in press*.

Abstract

The slatted floor system is popular in pig and cattle housing. Ammonia and odour are mostly emitted from the slurry pit under the slatted floor. In order to develop solutions to reduce this part of emissions, a better understanding of air distribution and pollutant transportation mechanisms is required. Computational fluid dynamics (CFD) is a useful technique to investigate the air motion, and transport of pollutants between room and pit headspaces via the slatted floor. However, there is a practical issue related to modelling the thousands of small slot openings in the real livestock building for CFD simulation. It is unrealistic to simulate the slatted floor with geometry details due to the large grid number and the limited computer capacity. In this study, a simplification model using porous media to represent a scaled slatted floor was developed. To assess the feasibility of this simplification, the proposed porous media model (SP) was compared with the direct geometry model (SD) and experimental data. The results showed that the porous media model was able to estimate the air velocities but not the turbulent kinetic energy. Both models predicted rotating flows under the slatted floor. A clear vertical air motion above the slatted floor was found for SP results but no such trend for SD results. The mechanism of the pollutant transportation, including the process of pollutant escaping from the pit and retention time of pollutant inside the pit headspace, was found to be inconsistent for SD and SP models. For SD, the dominant removal mechanism of transporting pollutants from the headspace to the free stream was mean flow transportation whereas it was turbulent flow transportation in SP. Higher emission rate and shorter retention time of pollutant in the headspace was obtained by using SP compared to SD. In general, though the porous media approach cannot reveal the pollutant transport mechanism, it can predict the velocity magnitude. In addition, it was found that the orientation of slats to stream flow direction plays an important role on airflow pattern and pollutant distribution inside the pit headspace.

Keywords: *CFD; slatted floor; porous media; pollutant transport*

7.1. Introduction

The slatted floor system is a type of floor with small slot openings which is quite popular being applied in the livestock industry. In a livestock building with a slatted floor system, pollutants like ammonia and odours are mostly emitted from the zone near the slatted floor, either the floor surface or the slurry pit under the floor (Zong, Feng, Zhang & Hansen, 2014; Zong, Zhang, Feng & Ni, 2014). Airflow patterns in the pit headspace and air exchange between pit and room space can significantly affect the ammonia dispersion which will further affect indoor air quality and emissions from the building (Morsing, Strom, Zhang & Kai, 2008). Therefore, a better understanding of the airflow characteristics and mass transportation mechanisms in the pit headspace is highly desired.

A number of experimental and numerical studies have been performed on the flow and transport of pollutants in livestock buildings (Tomas Norton, Grant, Fallon & Sun, 2009; Tomás Norton, Grant, Fallon & Sun, 2010) but have been limited to the space above the slatted floor. Detailed knowledge of the characteristics of airflow and mass transport under the slatted floor is still missing, although this is the key part to predict the gas emission from the slurry pit.

As described by Wu, Zong, and Zhang (2013), the investigated pit headspace was kind of a cubic cavity. The flow in such a cavity was featured with separation and known to be difficult to model. Other than the cavity flow in the pit headspace, similar research can be found in the area of modelling airflow in street canyons (Vardoulakis, Fisher, Pericleous & Gonzalez-Flesca, 2003). The prediction of airflow and pollutant dispersion within street canyons were commonly calculated using Reynolds-averaged Navier-Stokes (RANS) models. Among those turbulence models, the standard k-ε model is the most applied and has been proved to be an accurate model for the prediction (Baik & Kim, 2002; Johnson & Hunter, 1998; Kim & Baik, 2003; Neofytou, Venetsanos, Rafailidis & Bartzis, 2006; Sagrado, van Beeck, Rambaud & Olivari, 2002).

The cavity flow around a pit headspace is much more complicated than the above-mentioned investigations of street canyons due to the involvement of the slatted floor. Up until now, very few studies on modelling pit headspace are available in the literature. Wu, Zhang, Bjerg, and Nielsen (2012) applied different RANS models to study the airflow characteristics under slatted floor in a 1:2 pit model of a cattle building in which the slatted floor was simulated in geometrical details. However, in a full scale livestock building, modelling slatted floor directly in geometrical details is unpractical due to the large grid number and the computer capacity (Bjerg, Zhang & Kai, 2008b; Wu et al., 2013). The slot width in a real livestock building is up to 0.02 m while the building dimensions can be several thousand times larger. The big size difference between slot width and building dimensions including the ventilation openings prevents a direct modelling of the geometrical details for a full scale livestock building. Porous media was thus introduced to tackle this limitation in modelling slatted floor (Bjerg, Zhang & Kai, 2008a; Bjerg et al., 2008b; Sun, Keener, Deng & Michel, 2004). Up to date, the uncertainties of using porous media to simulate the slatted floor above the pit headspace have not been well documented, especially comparing with measured data. In the study of Wu et al. (2013), comparison of modelling slatted floor by using either geometrical details or as porous media was conducted, and results showed that the method of simulating slatted floor as porous media generally performed well. However, only the case in which the slats were oriented parallel to the flow direction was investigated (Wu et al., 2013). As we know, the direction of flow above the slatted floor can be different on the basis of the design of the building and air supply. For mechanically ventilated swine buildings with side wall air inlet, the dominant return airflow near the floor surface often has a direction perpendicular to the slat orientation (Zong, Feng, et al., 2014; Zong, Zhang, et al., 2014). An investigation of the case with the slats orientated perpendicular to the flow direction is necessary.

This study extends the investigation of airflow characteristics and ammonia dispersion around a pit headspace from a pilot study (Wu et al., 2013). The main purpose of this work is to assess the feasibility of modelling slatted floor as porous media in modelling airflow and pollutant dispersion in the pit headspace when the slats are oriented perpendicular to the flow direction. The numerical results are compared with the experimental results.

7.2. Materials and methods

7.2.1. Experimental setup

7.2.1.1. Wind tunnel and scaled pit model

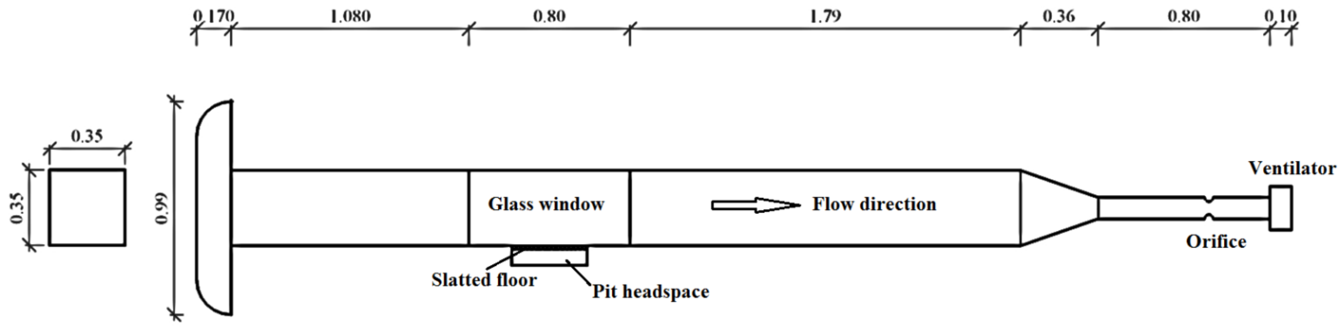
The experiments were conducted in a wind tunnel at Air Physics Lab, Aarhus University, Denmark. Fig. 7.1 shows the 3.67-m long wind tunnel configuration. The wind tunnel was made of polystyrene sheets and contained a 0.8m long transparent piece of glass to enable velocity and turbulence intensity measurements using a Laser Doppler Anemometer (LDA). A fan (Type CK125 C CBU, Lindab A/S, Denmark) was connected at the tunnel outlet to drive the air motion through the tunnel. Airflow went into the tunnel via a 0.17-m thick smooth surface contraction section fitted around the edges of the 0.35 (H) $\times$ 0.35 (W) m^2 wind tunnel cross section. Small neutrally buoyant particles made by the smoke generator (Z-series II, Antari Ltd., Taiwan) were injected into the wind tunnel inlet opening as the seeding for LDA to measure velocities.

A 1:8 scale pit model with a transparent front panel was constructed in the working section underneath the wind tunnel. The size of the scale model was 0.35 (L_p) $\times$ 0.35 (W_p) $\times$ 0.09 (H_p) m (Fig. 7.1b). The top of the pit model was covered by a slatted floor consisting of 17 slats. The slatted floor’s upper surface was at the same level with the tunnel floor surface. The slatted floor used in this study had an opening ratio of 23.38%. The dimensions of the slat are shown in Fig. 7.1b. It should be mentioned that the experimental setup using the pit model and wind tunnel was primarily used for the comparison of the two numerical approaches and not intend to predict the airflow dynamic characteristics in a full scale condition.

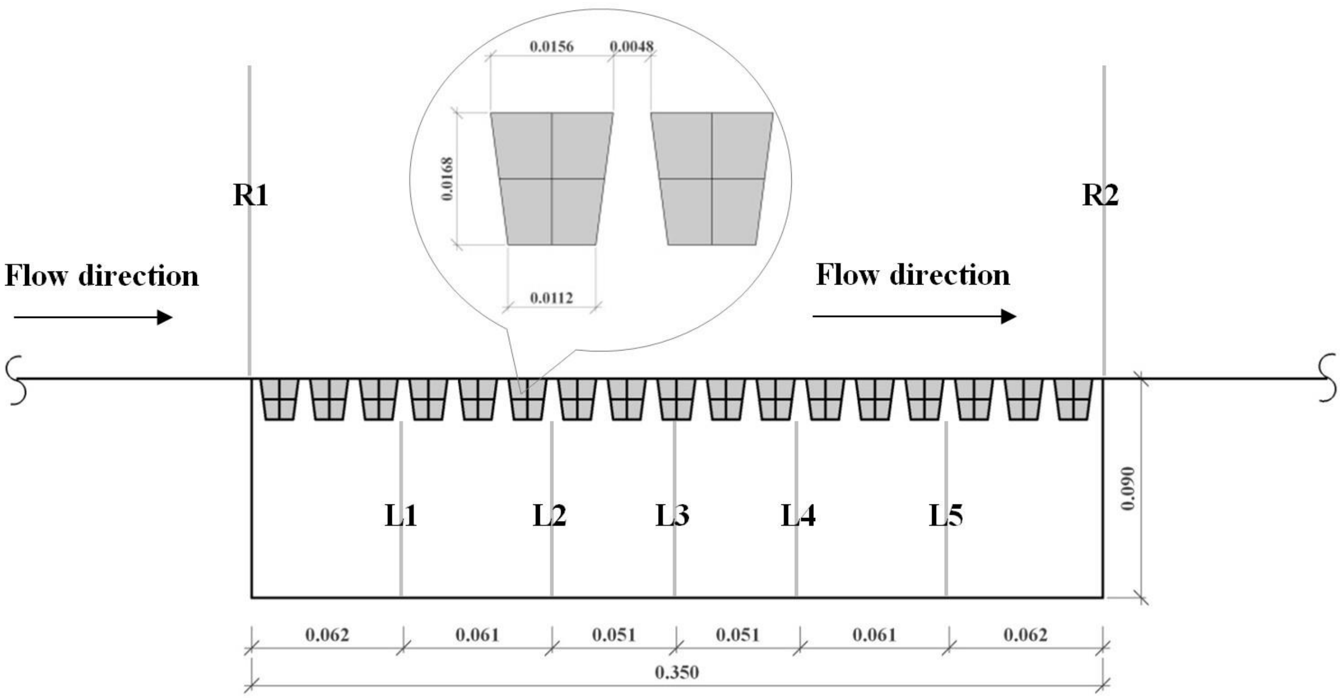
7.2.1.2. Air velocity and turbulence measurements

In this investigation, air velocities and turbulence intensities were measured by a 2-dimensional Laser Doppler Anemometer (FlowExplorer System, DANTEC Dynamics A/S, Skovlunde, Denmark). Two pairs of laser beams radiated from the transmitting/receiving optics could measure the velocity horizontally and vertically. The measurement distance from the lens was 285 mm.

Air velocity and turbulence intensity profile measurements were taken at 14 different vertical heights in the pit headspace (0.005, 0.010, 0.015, 0.020, 0.025, 0.030, 0.035, 0.040, 0.045, 0.050, 0.053, 0.058, 0.065, 0.070, and 0.073 m) and at five lines L1-L5 in the X-Y plane. In addition, air velocities at two lines (R1 and R2) with eight vertical heights (0.0925, 0.095, 0.1, 0.11, 0.115, 0.145, 0.175, and 0.265 m) above the pit area in the wind tunnel space were also recorded. All the measurement positions are in the middle plane of the wind tunnel (0.175 m away from the glass window). The distribution of all measurement positions is shown in Fig. 7.1b. Data acquisition period at each spatial position was 600 s.



(a)



(b)

Fig. 7.1: Schematic of (a) the wind tunnel; (b) the scaled pit model and slats (dimensions are in m).

7.2.2. Description of numerical model

In steady state Reynolds-averaged Navier-Stokes (RANS) modelling, the instantaneous quantity is decomposed into its time-averaged and fluctuating components. The RANS equations for incompressible Newtonian fluids are the following:

$$\frac{\partial \rho \overline{u_i}}{\partial x_i} = 0 \tag{1}$$

and

$$\overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \mu \frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} - \overline{u'_j \frac{\partial u'_i}{\partial x_j}} \tag{2}$$

where $\overline{u_i}$ and $\overline{u'_i}$ are the mean and fluctuating terms of the velocity component u_i in the x_i-direction, respectively. $\overline{p}$ is the mean pressure, ρ is the air density and μ is the viscosity.

In the present study, the standard *k*-*ε* model is employed. The standard *k*-*ε* model is based on two additional model transport equations for the kinetic energy (*k*) and its dissipation rate (*ε*). Commercial software Fluent 12.0 (ANSYS Inc., USA) was used to solve those equations. The second order upwind spatial discretization scheme was chosen for momentum, turbulent kinetic energy and turbulent dissipation rate. Standard and SIMPLE methods were employed for pressure and pressure-velocity coupling, respectively.

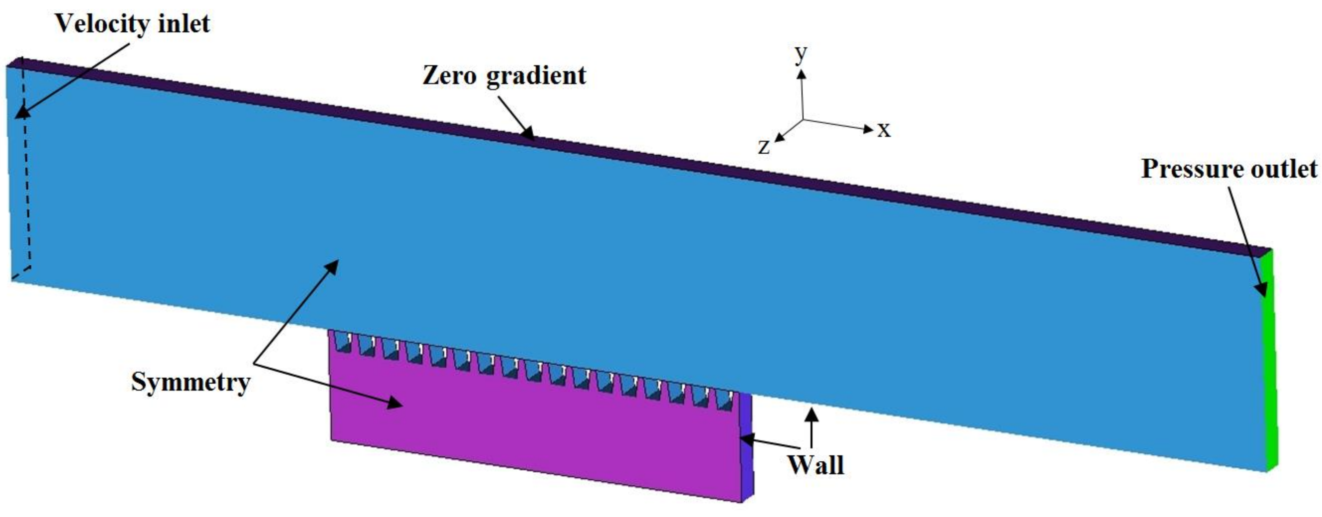
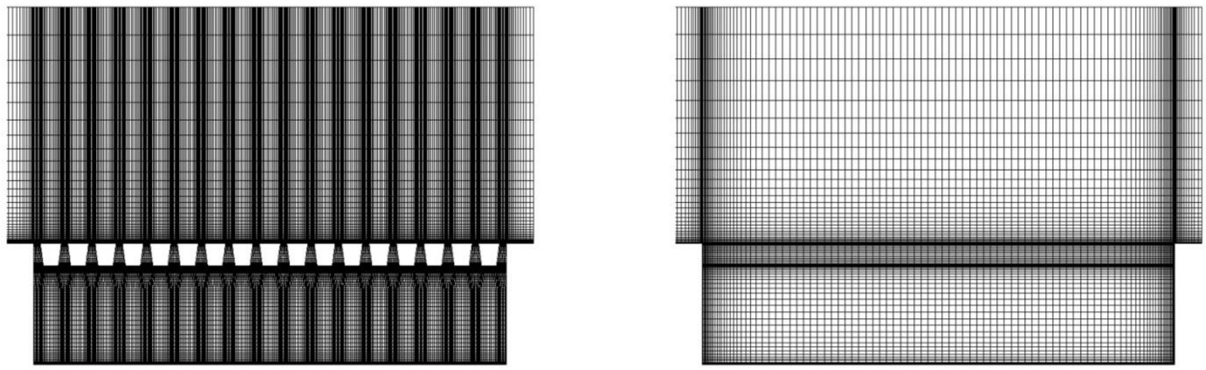


Fig. 7.2. The CFD domain with boundary conditions.

7.2.3. Computational domain and boundary conditions

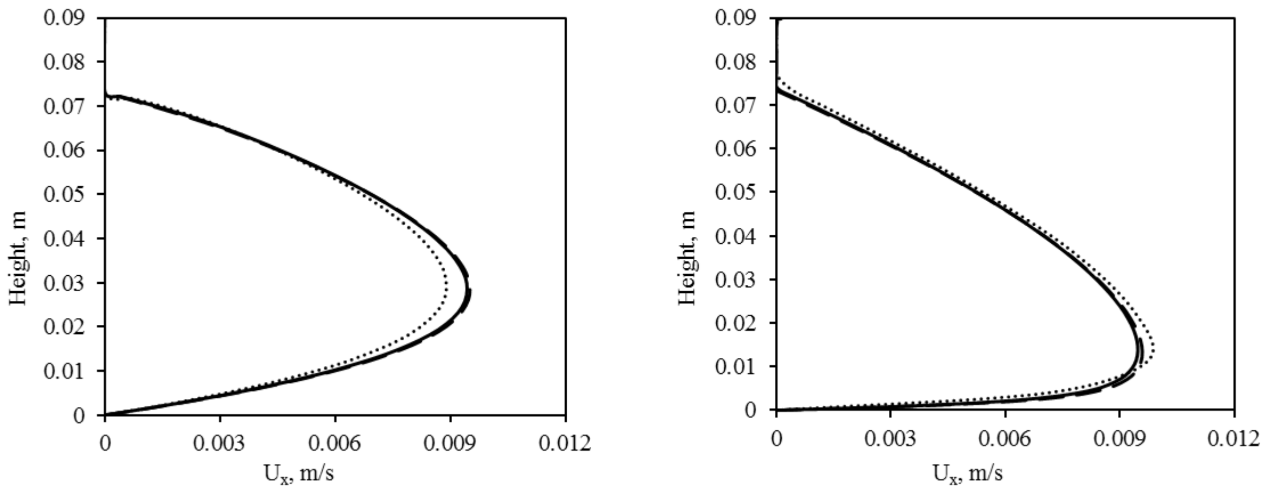
Fig. 7.2 shows the computational domain with boundary conditions. The domain was discretized using hexahedral elements. It was observed in the experiment that the velocity gradient was zero at

0.5H height of the wind tunnel. Therefore, the half-height of the wind tunnel space was used in the CFD model, and the height of the domain was 0.265 m (0.5H + 1H_p). The free surface layer for the upstream and downstream of the pit model was extended to 3H_p and 5H_p, respectively. The measured air speed at 0.5H height was 0.8 m s^{-1} which was used as the air inlet velocity (U). The associated Reynolds (Re) number was 1.92×10^4 based on the inlet velocity U and the height of the wind tunnel H. If the characteristic dimension of pit height accounted, the associated Re number would be 4.96×10^3. Both methods showed that the flow was a turbulent flow at low to medium Re number. Pressure outlet was set as the outlet boundary condition. The two domain sides along the flow direction were assumed to be symmetry planes which could, periodically, translate the domain along the direction perpendicular to the free streamlines. All the solid surfaces were treated as no-slip wall.



(a) **(b)**

Fig. 7.3. Pit model geometry with slatted floor (a) modelled directly and (b) treated as porous media.



(a) **(b)**

Fig. 7.4. Mesh convergence study of the velocities at L3 in (a) SD model and (b) SP model: dotted line – coarse mesh (Grid A); solid line – medium mesh (Grid B); dashed line – highest density mesh (Grid D).

Two modelling approaches were used to simulate the slatted floor: one using the floor's geometrical details directly including all the slats and slots, abbreviated SD; and another treating slatted floor as porous media, abbreviated SP (Fig. 7.3). In the SD model, the volume of the slats was defined as solid material while the volume of the slats and slots in SP is replaced by a square section of porous interior.

Grid independence was tested by constructing four types of meshes with different mesh density for each model as shown in Table 7.1. Grid A-D represent the meshes with coarse, medium, higher and highest mesh density, respectively. Fig. 7.4 shows the horizontal air velocities at different heights along the middle line (L3) predicted by Grid A, B and D. No significant changes can be seen from comparison between Grid B and D. As a result, Grid B of medium mesh was used for the following calculations which had 44,310 and 12,660 cells for the SD and SP model, respectively.

Table 7.1- Grid refinement, Grid A~D represents increasingly developed grids.

Grid	Grid A	Grid B	Grid C	Grid D
Grid number for SD	22,224	44,310	158,784	292,392
Grid number for SP	4,410	12,660	38,380	318,645

7.2.4. Modelling of porous media pressure drop

A flow resistance needs to be added to the porous cell zones representing the space of slats and slots in the SP model. Pressure drop was thus formed when air went through the cell zones with resistance. In the commercial CFD software Fluent 12 (ANSYS, Inc., USA), flow resistance along the porous thickness as a volume-based sink term can be calculated using the following momentum equation:

$$\frac{dp}{dx} = C_v \cdot \mu U + F_i \cdot \frac{1}{2}\rho U|U| \tag{3}$$

where dp/dx is the pressure drop over the porous media, U is the superficial velocity through the porous media, ρ is the air density, μ is the air viscosity, C_v and F_i are the viscous resistance coefficient and the internal resistance factor, respectively. In this investigation, C_v and F_i are unknown constants to be determined along the thickness of the slatted floor.

The approach to obtaining the constants C_v and F_i is as follows: first, a well resolved grid, then isothermal simulations are performed for air inlet at different levels (0.1, 0.2, 0.5, 0.8, 1.4, 2 and 4 m s^{-1}). After the seven flow simulations are conducted, the pressure gradients above and below the slatted floor (entrance and exit sections of the porous section) are computed for each flow. By applying Eq. (3), the constants C_v and F_i were obtained with a curve fitting the simulated results (Fig. 7.5).

Therefore, the resistance of the porous zone was taken as 4.89×10^7 m^{-2} for the viscous resistance coefficient and 2.64×10^5 m^{-1} for the inertial resistance factor along the vertical flow (y-direction). The resistances to flow across the side (z-direction) were set to be equal to the resistant values along the vertical direction whereas the resistances to the horizontal flow (x-direction) were considered to be much higher and set to values a thousand times bigger than those along the vertical flow (y-direction).

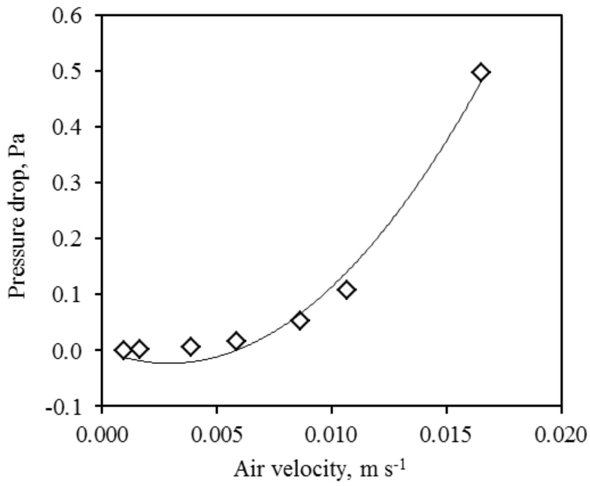


Fig. 7.5. Relationship between air velocity and pressure drop through the slatted floor determined in CFD simulation with geometric details: diamond - the simulated results; solid line - the selected values of $C_v = 4.89 \times 10^7$ and $F_i = 2.64 \times 10^5$ using Eq. (3) matching the simulated results.

In this study, the constants C_v and F_i are obtained from numerical simulations, as it is difficult to measure the superficial velocity and pressure drop through the slatted floor. However, a better solution would be obtaining these values experimentally using wind tunnel facilities, which is expected to be investigated in future study.

7.2.5. Modelling of pollutant transportation

7.2.5.1. Pollutant transport approach

In this study, ammonia is considered as the pollutant. The convection-diffusion approach was used for the pollutant dispersion which was simulated by the scalar transport equation. The transport equation for NH_3 is written as (Baik & Kim, 1999):

$$\frac{\partial \overline{C}}{\partial t} = \nabla \cdot (D_m \nabla c) - \nabla \cdot (\overline{v} \cdot \overline{C}) + S_c \tag{4}$$

where $\overline{C}$ is the mean concentration of a passive pollutant, t is the time, $\overline{v}$ is the mean velocity, D_m is the mass diffusivity for the scalar variable, S_c denotes the source or sink term of the pollutant, which was set as constant species mass fraction of NH_3 in the simulations, ∇ represents gradient and $\nabla \cdot$ represents divergence.

In porous media, the effective diffusion coefficient is used to describe actual diffusion through pores (Grathwohl, 1998).

$$D_e = \frac{D_m \varepsilon_t \delta}{\tau} \tag{5}$$

where D_e is the effective diffusion coefficient in gas filling the porous media, ε_t is the porosity and equals 0.343 based on slatted floor dimensions, δ is the constrictivity which was set at the same value as the porosity, τ is the tortuosity which can be estimated as the ratio of the length of the tortuous curve to the distance between the ends of the curve. The tortuosity was 1.27 in this case.

D_m is the mass diffusivity in the mixture air and can be estimated by:

$$D_m = \frac{10^{-7} T^{1.75} * (1/M_{NH3} - 1/M_{air})^{1/2}}{p(20.1^{1/3} + 14.9^{1/3})^2} \tag{6}$$

where M is the molecular weight, p is the atmospheric pressure (atm), T is the air temperature (K). Further details of Eq. (6) can be found in the paper by (Sommer et al., 2006).

7.2.5.2. Vertical mean and turbulent mass flux

An instantaneous velocity u can be decomposed into a mean flow component $\bar{u}$ and a fluctuation component u'. The vertical flux of the pollutants by mean flow (mean flux, F_m) and the vertical flux of pollutants by turbulent flow (turbulent flux, F_t) were calculated using (Baik & Kim, 2002)

$$F_m = CU_y \tag{7}$$

$$F_t = c'u'_y = -K_c \frac{\partial C}{\partial y} \tag{8}$$

where c' and u_y' are the deviations from the mean NH_3 mass fraction C and mean vertical velocity U_y at the slatted floor level, respectively. K_c is the turbulent diffusivity for the scalar variable and could be calculated by

$$K_c = \frac{C_\mu k^2}{Sc_t \varepsilon} \tag{9}$$

where C_μ is a constant (= 0.09), k is the turbulent kinetic energy, ε is the turbulent dissipation rate, Sc_t is the turbulent Schmidt number and specified as 0.9 (Sini, Anquetin & Mestayer, 1996).

The investigation of F_m and F_t may help to find the difference between transportation mechanisms through the slatted floor simulated directly and simulated as a porous zone (Wu et al., 2013).

7.2.5.3. Retention time

The pollutant retention time is used to identify the consistency of the time scale of pollutant residing under the slatted floor (Liu, Leung & Barth, 2005; Wu et al., 2013). The retention time Γ_{Ω} is calculated by

$$\Gamma_{\Omega} = \frac{\theta_{\Omega}}{Q} \tag{10}$$

where θ_{Ω} and Q represent the total mass of pollutant in the pit headspace and the pollutant emission rate, respectively. In the simulation, the mass of pollutant was determined by mass fraction $\times$ area $\times$ air density $\times$ velocity.

7.3. Results and discussion

7.3.1. Model validation

7.3.1.1. Comparison of air velocity profiles

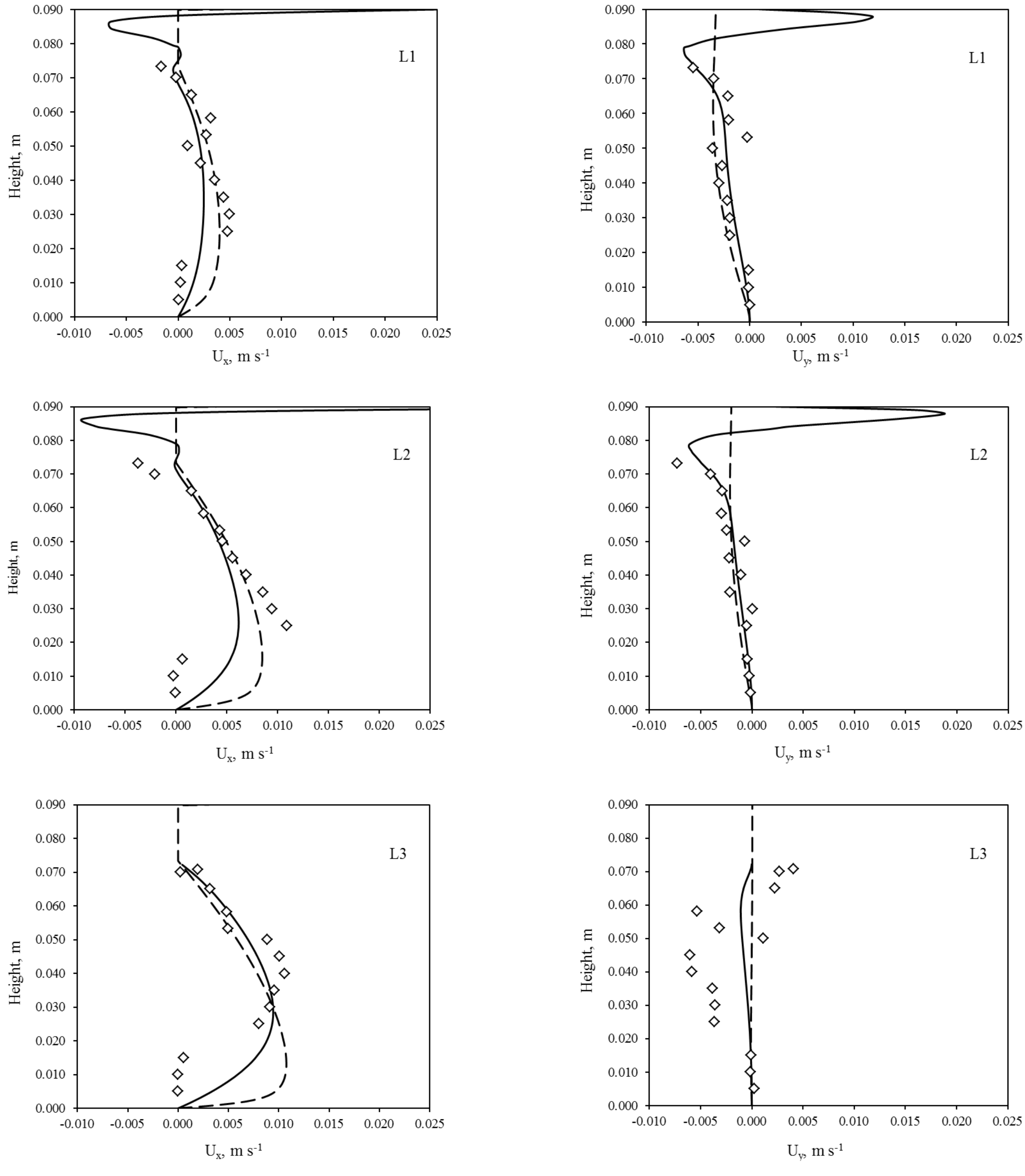
Air velocities in the pit headspace were very low compared to the air velocity above the slatted floor with the maximum velocity of 0.01 m s^{-1} under the slatted floor. Fig. 7.6 shows the vertical profiles of the mean velocities obtained from the direct geometry model (SD) and the porous media model (SP) together with measurement data in the pit headspace. At L1 and L2 near the upwind pit wall, both SD and SP results achieved very good prediction both on the shape of the velocity profile and on each velocity component (U_x, U_y). In the middle of the headspace (L3), both simulations provided consistent horizontal air velocities in line with the measured values, but the vertical air velocities could not match the measured results. Next to the downwind pit wall (L4 and L5), the SD model overpredicted the horizontal air velocities at most locations while the SP started off well near the upper pit headspace but then diverged from the experimental results towards the headspace bottom. Both SD and SP underpredicted the vertical air velocities at L4 but overpredicted the vertical air velocities at L5.

The discrepancies between the simulated and the measured values were also analysed (Table 7.2a and 2b), which can be expressed as relative errors defined as:

$$Error(\%) = abs\left(\frac{v_m - v_s}{v_m}\right) \tag{11}$$

where v_m and v_s represent measured and simulated values, respectively.

The relative error values at different measurement locations varied a lot. Since the air velocity level in the pit headspace was very low, some of the relative errors were quite large even though the differences between the measured and predicted values were small. Desired agreements between simulation and measurements of both horizontal and vertical air velocities were observed in L1, L2 and L3 at heights ranging from 0.025 m to 0.065 m. Relatively large discrepancies occurred in L4 and L5 and also at the heights near the bottom of pit headspace. The limitation of the current velocity measurement instrument when measuring near wall locations could be one of the reasons for the large relative errors near the pit bottom. In general, SD got more consistent results compared to SP. In addition, Table 7.2a and 2b also present the root mean squares (RMSs) of the differences between simulated and measured air velocities and the means of absolute measured velocities in the five measuring lines. The RMS of the horizontal velocity prediction errors varied between 0.0015 and 0.0083 m s^{-1} while the RMS of the vertical velocity errors varied between 0.0009 and 0.0058 m s^{-1}. The mean absolute horizontal velocities in the measured lines range between 0.0015 and 0.0051 m s^{-1}, and the vertical velocity means ranges between -0.0010 and 0.0030 m s^{-1}. The highest absolute horizontal and vertical air velocity means were found in L3.



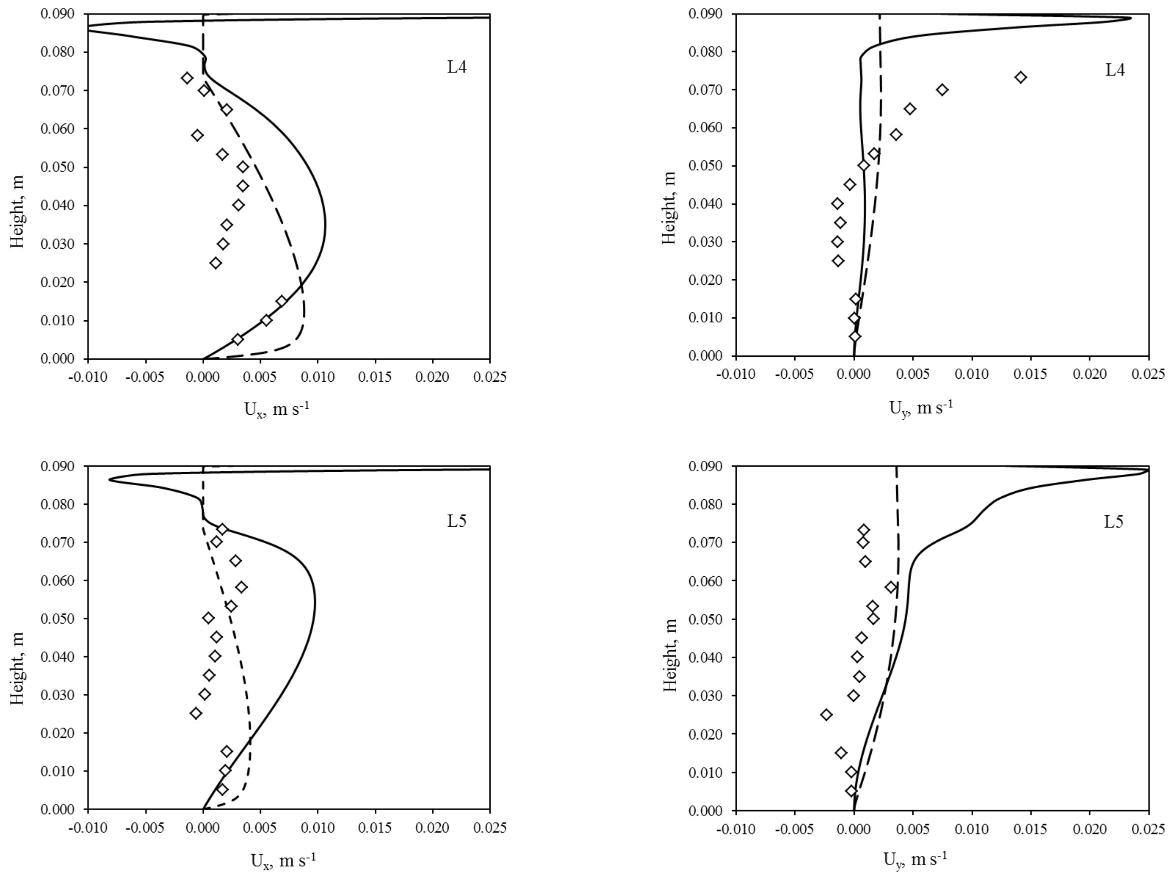


Fig. 7.6. Vertical profiles of air velocity in the pit headspace: diamond – measured value; solid line – simulated values by modelling SF directly; dashed line – simulated values by treating SF as porous media.

7.3.1.2. Comparison of profiles of turbulent kinetic energy

Fig.7.7 shows the vertical profiles of turbulent kinetic energy in the pit headspace. The SD results agreed well with the measured results at almost all locations whereas the SP results diverged more, comparatively, from the measured results. The turbulent kinetic energy predicted by SP increased with height, and the value was higher on the downwind side than on the upwind side. This phenomenon was in accordance with a previous cubic cavity study where no cover was put on the cavity top (Baik & Kim, 1999). However, the turbulent kinetic energy obtained by SD kept very small for all the area in the pit headspace except the near floor region. The turbulent kinetic energy calculated by SP could be up to ten times that calculated by SD in the slot (y = 0.09 m).

Table 7.2a Relative prediction error of U_x comparison of the simulation and the measurement, %. SD: direct geometry; SP: treating as porous media; RMS: root mean square of the difference of simulated and measured values; $U_{x\text{-}mm}$: means of measured velocity in x-direction (horizontal).

y, m	L1		L2		L3		L4		L5		Means	
	SD	SP	SD	SP	SD	SP	SD	SP	SD	SP	SD	SP
0.005	1555	4555	4648	13212	64590	185511	8	164	161	305	14193	40750
0.010	524	1336	1809	3453	26458	47775	6	58	209	300	5801	10584
0.015	400	894	705	1178	1244	1774	5	28	259	295	523	834
0.025	55	17	46	23	10	31	668	648	671	594	290	263
0.030	53	20	35	14	2	10	463	365	3420	2412	795	564
0.035	44	10	29	10	1	1	405	267	1365	803	369	218
0.040	31	1	22	5	18	26	239	102	900	395	242	106
0.045	6	49	13	4	22	31	183	55	853	328	216	93
0.050	122	203	8	8	22	34	160	31	2098	588	482	173
0.053	30	6	13	1	27	5	400	138	489	183	192	67
0.058	53	36	7	24	6	17	1616	752	389	147	414	196
0.065	58	11	8	22	1	28	118	18	394	130	116	42
0.070	28	322	112	137	451	281	1628	468	561	129	556	267
0.073	74	103	96	102	100	98	154	102	234	102	132	101
Means	217	540	539	1300	6639	16830	432	228	857	480	1737	3879
RMS (m/s)	0.0015	0.0017	0.0028	0.0039	0.0029	0.0050	0.0056	0.0038	0.0083	0.0043	0.0042	0.0037
$U_{x,mm}$, (m/s)	0.0022		0.0044		0.0051		0.0026		0.0015		0.0029	

Table 7.2b Relative prediction error of U_y comparison of the simulation and the measurement, %. SD: direct geometry; SP: treating as porous media; RMS: root mean square of the difference of simulated and measured values; $U_{y\text{-}mm}$: means of measured velocity in y-direction (vertical).

y, m	L1		L2		L3		L4		L5		Means	
	SD	SP	SD	SP	SD	SP	SD	SP	SD	SP	SD	SP
0.005	822	2441	66	52	97	83	144	222	142	282	254	616
0.010	243	784	31	97	131	156	658	1255	251	493	262	557
0.015	601	1426	18	81	195	182	351	548	167	226	266	493
0.025	53	9	13	109	104	102	59	31	153	178	76	86
0.030	36	12	1390	2188	107	102	48	15	6332	7807	1583	2025
0.035	30	16	53	31	110	102	29	18	413	449	127	123
0.040	33	2	32	66	111	100	33	28	4057	913	253	222
0.045	19	22	27	13	113	100	195	543	525	417	176	219
0.050	35	4	164	197	16	101	196	346	159	108	114	151
0.053	868	1314	23	17	132	99	143	223	182	125	270	355
0.058	23	73	30	29	121	99	117	161	48	18	68	76
0.065	49	68	7	27	65	102	111	148	417	283	130	125
0.070	24	2	3	47	95	102	108	130	760	379	198	132
0.073	5	37	34	71	100	101	104	116	981	354	245	136
Means	203	444	135	216	107	109	164	270	828	859	287	380
RMS (m/s)	0.0009	0.0012	0.0009	0.0016	0.0040	0.0036	0.0049	0.0058	0.0036	0.0024	0.0029	0.0029
$U_{y,mm}$ (m/s)	0.0020		0.0019		0.0030		0.0027		0.0010		0.0022	

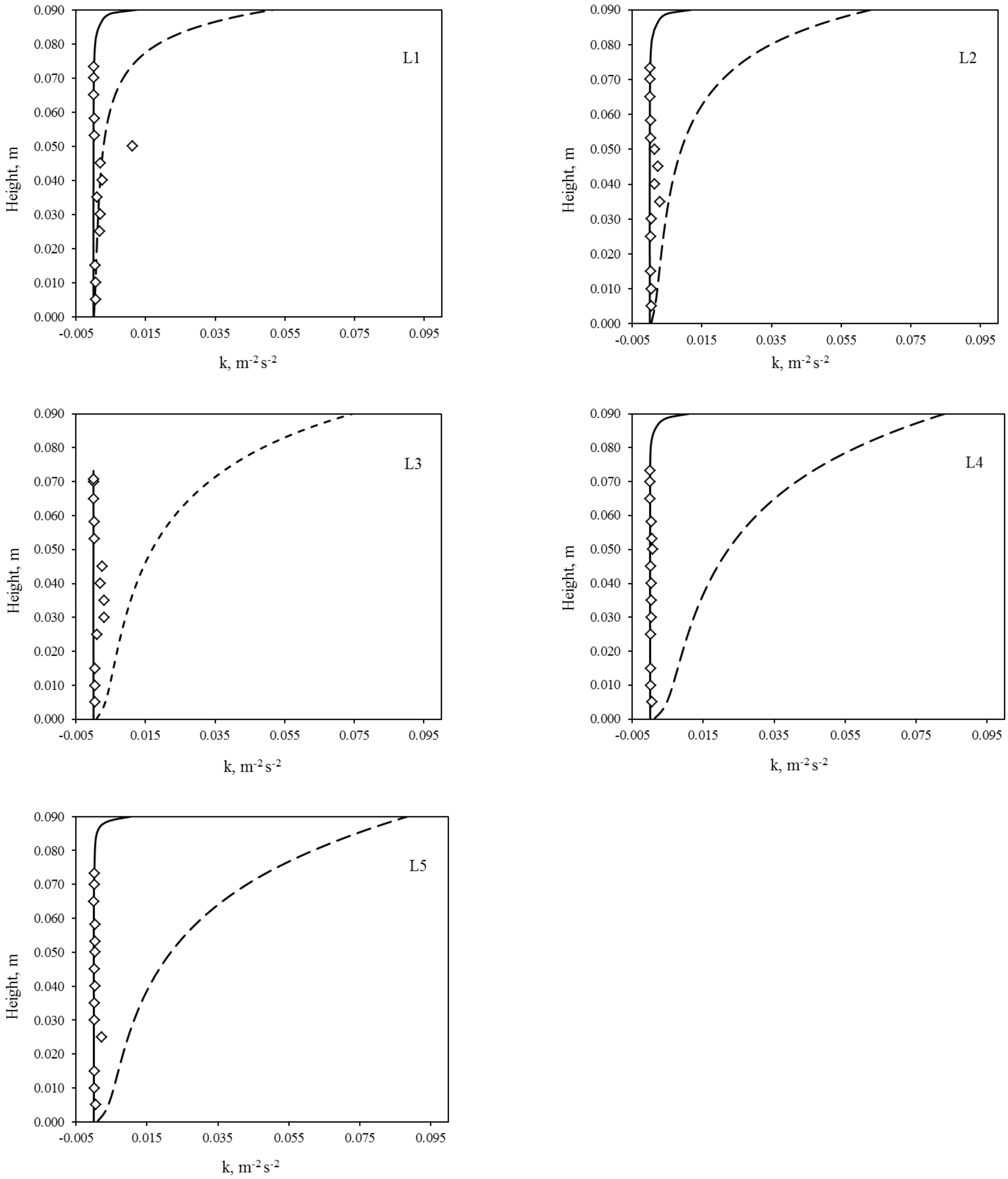


Fig. 7.7. Vertical profiles of turbulent kinetic energy in the pit headspace: diamond – measured values; solid lines – simulated values by modelling SF directly; dashed line – simulated values by treating SF as porous media.

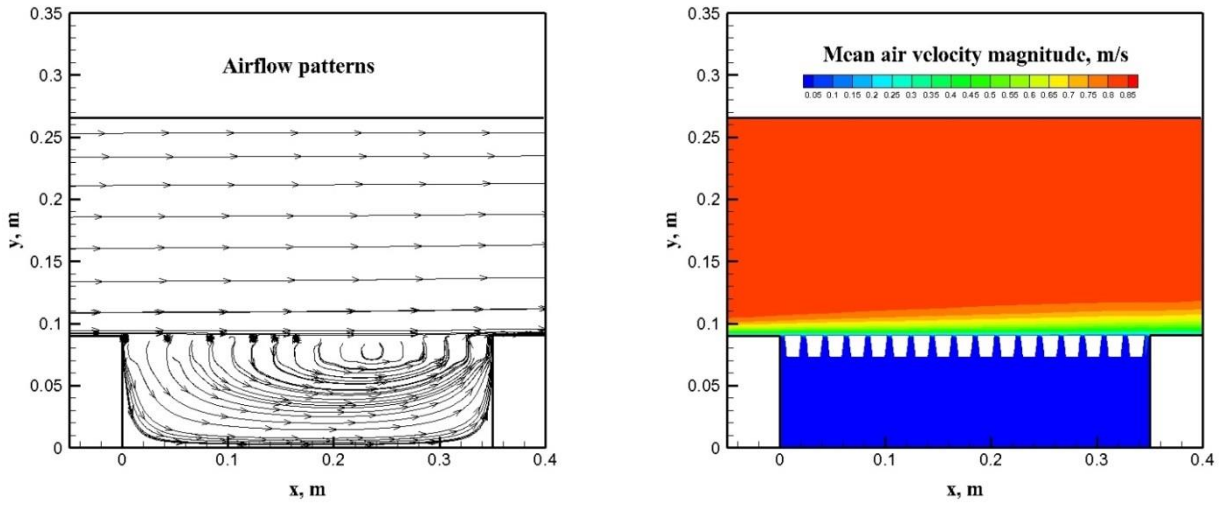
7.3.2. Airflow pattern and NH_3 distribution in the pit headspace

Fig. 7.8 depicts the airflow patterns, velocity magnitude and ammonia fraction in the pit headspace obtained by simulations of SD, SP and the experimental results. Both modelling approaches and the experiment got a significant anticlockwise circulation in the headspace. The air dropped into the pit on the upwind side climb up on the downwind side. In SD, the vortex centre was at x = 0.24 m. Meanwhile in SP, the vortex centre shifted back to x = 0.175 m which was also the centre of the pit headspace.

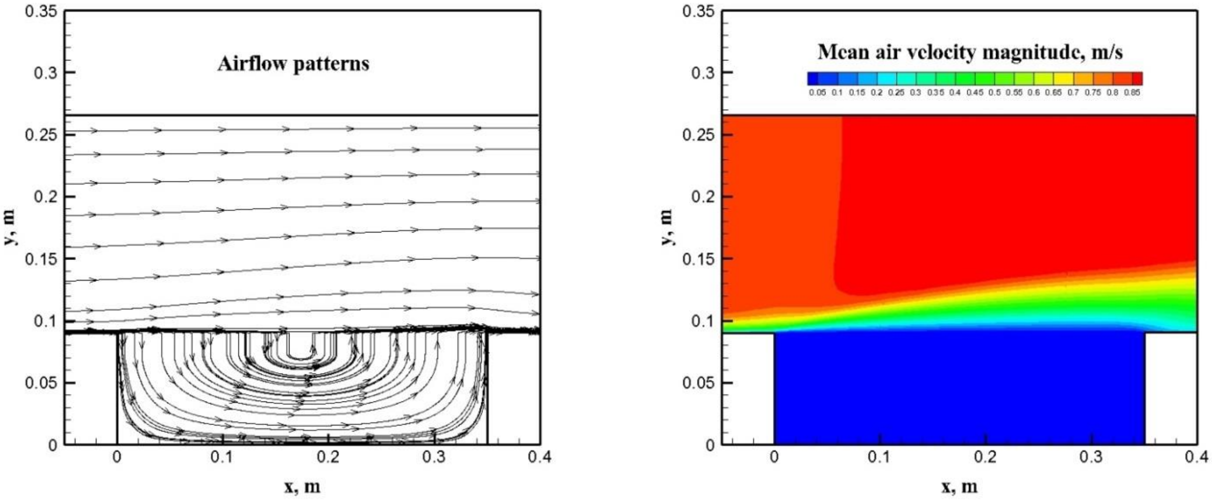
Another difference to be noticed between the two modelling approaches is the airflow pattern in the free airstream above the slatted floor (Fig. 7.8). For SP results, there was significant and increased vertical movement along the airstream in the tunnel space. However, for the SD results, the air above the floor surface was generally smooth and no significant vertical movement was observed, which was similar with experimental results (Fig. 7.8). Fig. 7.10 illustrates the detailed vertical velocity profiles at line R1 and R2 which also represent the region before and after the pit area in the wind tunnel space. Both the SD and SP models could predict the horizontal velocities in the tunnel. Generally, the vertical velocities estimated by the SD model could match the experimental results except at the height of y = 0.265 m, which could be caused by the 3-D momentum created by the ventilator. A significant difference between the SD and SP model was found in the vertical air velocity. For the SP model, there was uptrend air near the floor region before air enters the pit and a downtrend air after air exits the pit along the airstream in the wind tunnel.

Higher concentration of NH_3 was found on the downwind side of the pit headspace (Fig. 7.9). This is different from most street canyon studies and the pilot study investigating the slats placed parallel to the flow direction (Wu et al., 2013) which found a higher concentration of pollutants on the upwind side rather than on the downwind side. The transport and distribution of pollutants are dependent on the airflow development inside the cavity. In this study, the circulated flow in the pit headspace was anticlockwise. However, clockwise circulations were found in previous studies where free airstream was likely to enter the cavities at the downwind side since there was no cover on the cavity top or the slot opening parallel to the flow direction.

(a)



(b)



(c)

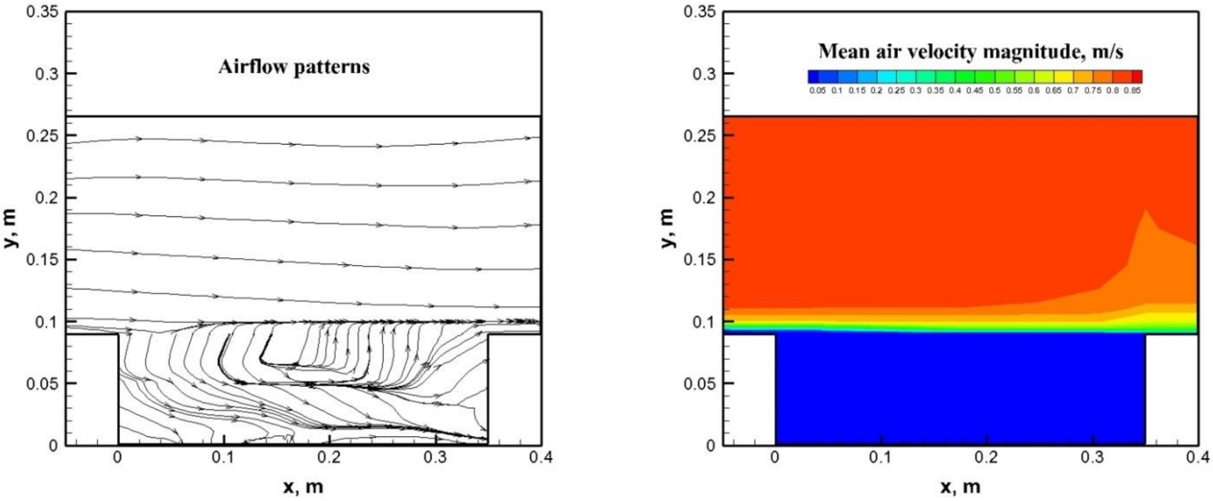


Fig. 8. Airflow patterns, velocity magnitude in the pit headspace: (a) modelling SF directly; (b) treating SF as porous media; and (c) experimental results.

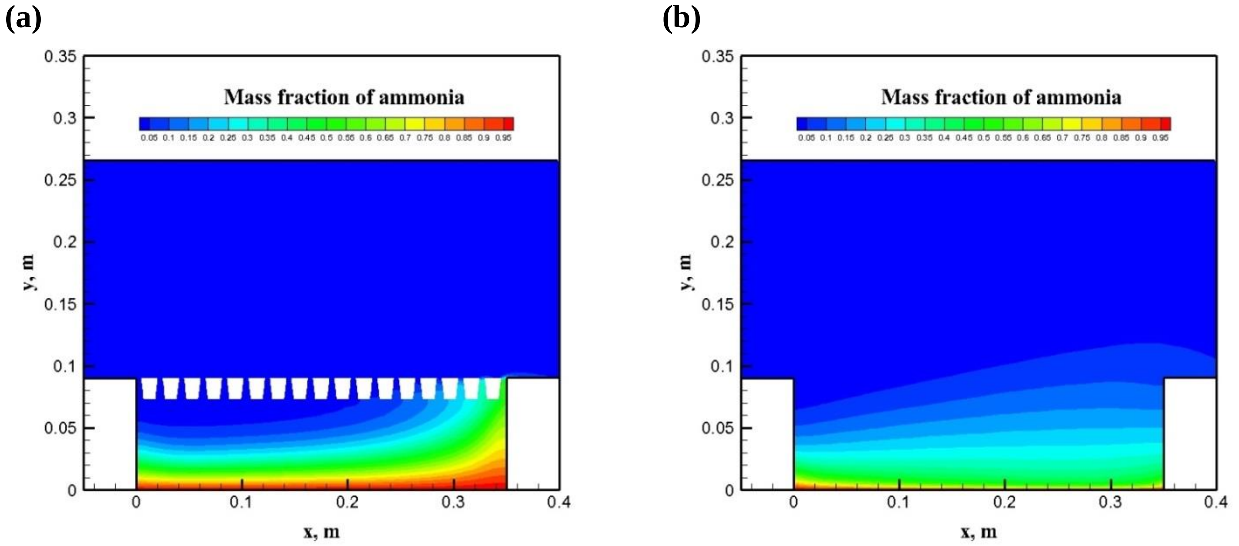


Fig. 7.9. Mass fraction of ammonia in the pit headspace: (a) modelling SF directly and (b) treating SF as porous media.

7.3.3. Comparison of pollutant transport prediction between the two simulation approaches

The process responsible for pollutant escaping from the pit headspace is presented and discussed in this section based on the investigations. At the slatted floor up-surface (y = 0.09 m), horizontal distribution of vertical velocities, turbulent kinetic energy, NH_3 concentration (*C*) and its vertical gradients ($\partial C/\partial y$) were demonstrated in Fig. 7.11. A significant difference appeared in the above-mentioned distributions between the two simulation approaches. For both SD and SP, the vertical air was in a downward flow on the upwind side, and it decreased to zero and became an upward flow on the downwind side (Fig. 7.11a). The simulated vertical air speeds along the top of the pit were much higher in SD than in SP, especially near the downwind pit wall. There was a relatively strong updraft in the region near the downwind pit wall (x = 0.35 m), which resulted from the flow in the pit headspace impinging on the downwind pig wall. The turbulent kinetic energy in the SP model gradually increased from the upwind side to a downwind position of x = 0.31 m and then decreased rapidly near the downwind pit wall (Fig. 7.11b). In the SD model, the turbulent kinetic energy was relatively small (< 0.014 $m^2 s^{-2}$) and changed very little across the slatted floor up-surface. At the top of the pit, the NH_3 concentration increased along with the flow stream for both SD and SP (Fig. 7.11c). However, rather than gradually increasing in SP, the concentration in SD was very small for most regions, except for the region near the downwind pit wall where it rapidly increased up to the edge. The vertical gradient of the NH_3 concentration is negative everywhere across the top of the cavity for both approaches (Fig. 7.11d). This is consistent with previous studies (Baik & Kim, 1999, 2002; Wu et al., 2013). The vertical gradient was very small except for the region close to the downwind pit wall in SD where its magnitude was large (Fig. 7.11d).

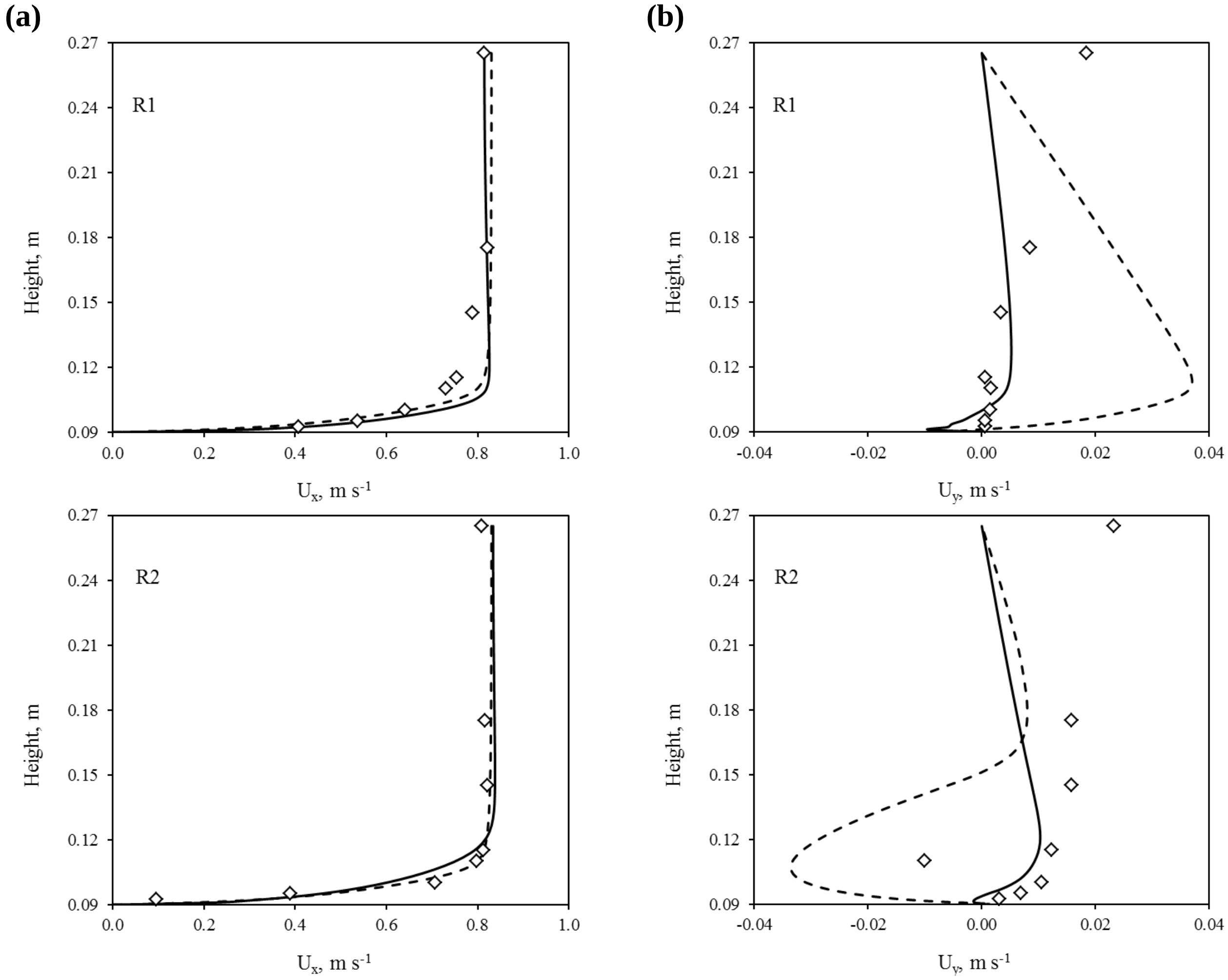
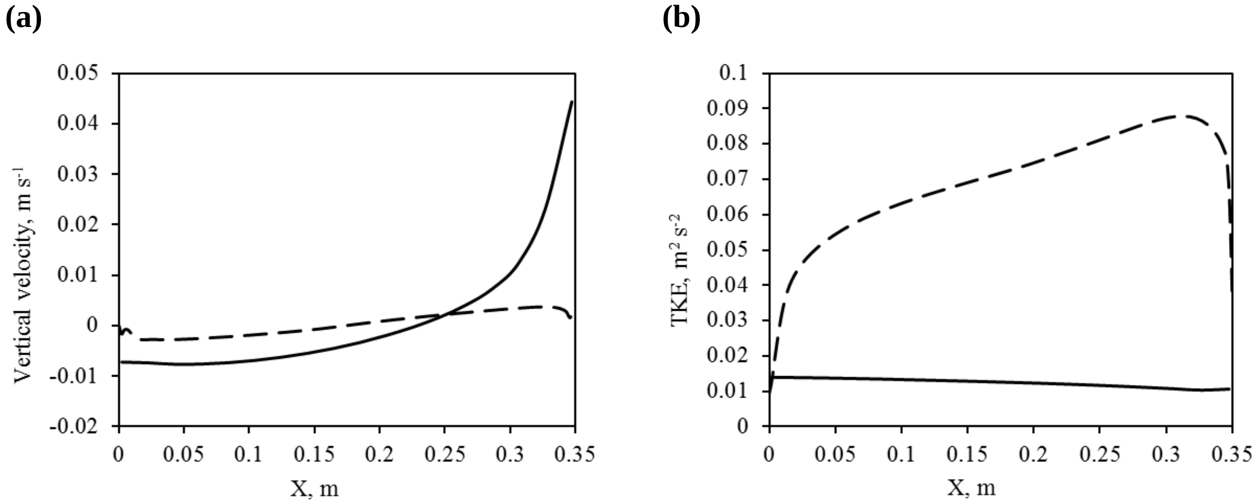


Fig. 7.10. Vertical profiles of air velocity in the wind tunnel: diamond – measured value; solid line – simulated values by modelling SF directly; dashed line – simulated values by treating SF as porous media: (a) modelling SF directly and (b) treating SF as porous media.



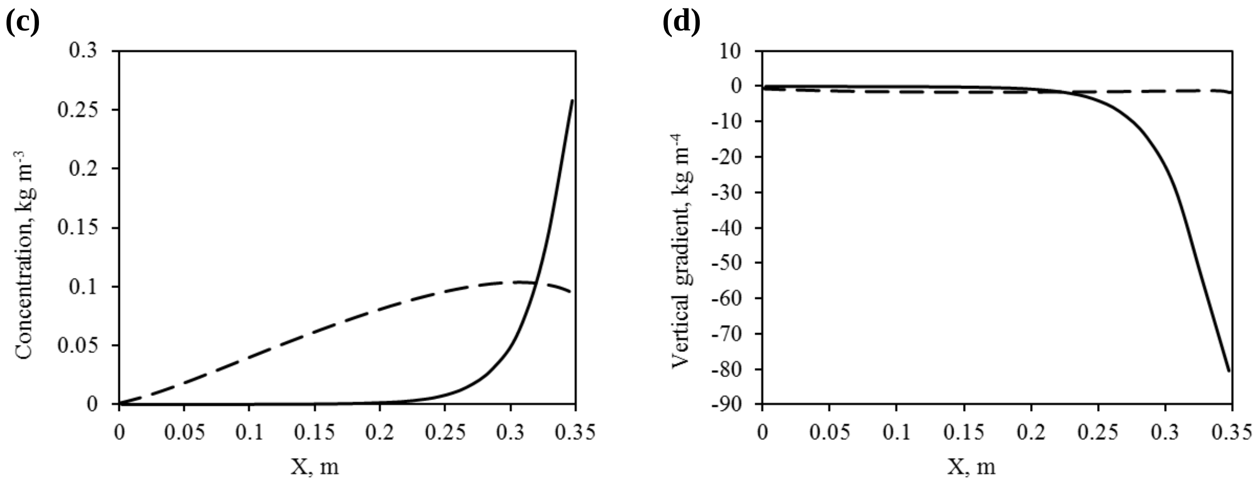


Fig. 7.11. Horizontal distributions of (a) vertical velocity, (b) turbulent kinetic energy, (c) NH_3 concentration and (d) vertical gradient of pollutant concentration ($\partial C/\partial y$) at y = 0.09 m; solid line – SD (averaged values in the slot); dashed line - SP.

Fig. 7.12 shows the horizontal distribution of the vertical NH_3 flux transported by the mean vertical flow U_y and the turbulent flow u'_y in SD and SP. The horizontal patterns of vertical flux were very different in SD and SP. For SD, both vertical mean and turbulent fluxes along the top of the pit headspace were very small except for the region near the downwind pit edge where they became large. The maximum removal of pollutants happened at position x = 0.35 m for both kinds of flux in SD. However, only the mean vertical flux kept very small in SP which was negative on the upwind side and positive on the downwind side. The turbulent flux in SP gradually increased from the upwind side to a downwind position of x = 0.31 m which was also the position with maximum turbulent kinetic energy and then decreased slightly. For SD, the dominant pollutant removal was via mean flow (80.8%) whereas in SP, turbulent flow removed most pollutants (80.4%).

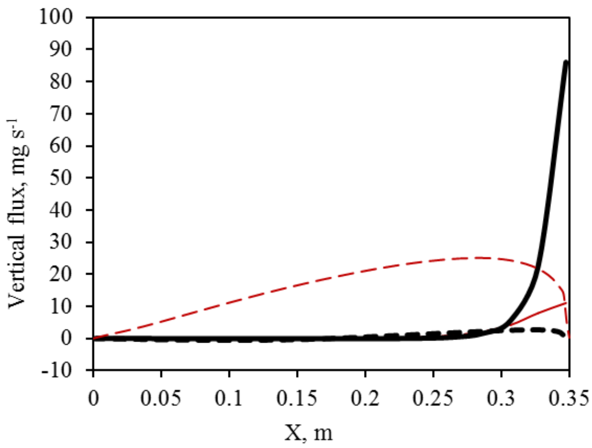


Fig. 7.12. Horizontal distribution of vertical mean flux and vertical turbulent flux of ammonia: Solid and dashed lines denote results of SD (averaged values in the slot) and SP, respectively; Thick and thin lines mark ammonia transport by mean flux and turbulent flux, respectively.

Retention time defined by Eq. (10) was used to investigate the time scale of the NH_3 residing in the pit headspace. Table 7.3 shows the NH_3 emission rate, total mass of NH_3 confined in the pit headspace and the retention time. The total mass of NH_3 confined in the headspace determined by SD and SP was close to each other. Nevertheless, the emission rate from the pit calculated by SP was double that of SD. The retention time for SP was therefore only half of that for SD.

Table 7.3 Emission rate, total mass in the pit headspace and retention time of NH_3 from simulations.

Modelling method	Emission rate (mg s-1)	Total mass in the pit headspace (mg)	Retention time (s)
SD	7.99	187	23.4
SP	14.53	158	10.9

7.3.4. Summary of findings

We start by comparing the vertical profiles of air velocities and turbulent kinetic energies in the pit headspace to examine the performance of two numerical approaches to modelling the airflow and pollutant transportation under slatted floor. Similar predictions in both horizontal and vertical velocities were found for the two approaches. Velocity results from both simulations were well validated by the measured values, especially near the upwind region. However, a notable difference occurs in the turbulent kinetic energy for the SP model which was much bigger than that of the SP and the measurements. We also found a similar prediction for the two approaches in airflow pattern and contour plots.

The mechanism of the pollutant transportation, including the process of pollutant escaping from the pit headspace and the time scale for pollutants residing in the cavity, was found to be inconsistent for SD and SP. One explanation could be the change of the length scale when applying porous media to replace the slatted floor zone. In the direct geometry approach, the narrow slot could decompose the airflow to small eddies, which makes the turbulent kinetic energy cascade and dissipate. Another reason could be the change of diffusivity in the porous media, which becomes smaller in the pores compared to that in the real slot. Correction of mass diffusion in the porous zone needs to be considered in the perspective work.

Generally, the porous media approach provided predictions of velocity that are in agreement with the direct geometry approach, but it failed to reveal the mass transport mechanism from pit to free air stream. The computational CPU savings are about 71% in this particular scale model case. Further utilization of porous media in real livestock buildings is likely to get even higher CPU savings as the ratio of slat to the building is much bigger. Although porous media have been applied for CFD simulation of livestock buildings in some studies and have gotten acceptable results (Bjerg et al., 2008b; Sun et al., 2004; Wu, Zhai, Zhang & Nielsen, 2012), the inaccurate prediction on mass transport using porous media needs to be taken into account in future studies.

This work is an extension of earlier research on the case with slats oriented parallel to the stream flow direction (Wu et al., 2013). It was found that the orientation of the slats could affect the airflow pattern and pollutant distribution inside the pit headspace significantly. The flow under the slatted floor oriented parallel to the stream flow direction is a clockwise-rotating vortex whereas it is an anticlockwise-rotating vortex under the slatted floor oriented perpendicular to the stream flow direction. The spatial distribution of pollutant concentration shows opposite patterns across the pit headspace for the two cases. In the earlier parallel case with the direct model, the pollutant escaping from the pit is mainly due to turbulence flow flux. In contrast, mean flow flux plays a major role in pollutant escaping from the pit in the current perpendicular case with the direct model.

7.4. Conclusion

In this study, the adequacy of using a porous media approach to simulate the slatted floor was investigated. Two numerical approaches were proposed: one applied direct geometry model for the slatted floor (SD) and another used porous media model (SP). The following conclusions can be drawn from the results:

- The SP approach yields predictions comparable to the SD approach on air velocities in the pit headspace. The results of velocity from both approaches can be well validated by measurement, especially on the upwind side. The turbulent kinetic energy cannot be well predicted for most locations with the SP model.
- An anticlockwise-rotating flow in the cavity was observed by both the SD and SP model. There is a small shift of vortex-center between two models. There was a clear vertical air motion in the tunnel space above the slatted floor for the SP results, but no such trend was found for the SD results. There was a higher concentration of NH_3 distributed on the downwind side for both approaches.
- There were significant differences between the results from the two approaches in relation to the process of pollutant dispersion from the pit headspace. For SD, the dominant removal mechanism for transporting pollutants from the headspace to the free stream was mean flow transportation whereas it was turbulent flow transportation in SP. The total mass of NH_3 in the pit headspace calculated by the SD and SP models was close to each other. Pollutants with higher emission rate and shorter retention time in the pit headspace were observed when using SP compared to using SD.
- The orientation of slats in relation to the stream flow direction plays an important role for airflow pattern and pollutant distribution inside the pit headspace.

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Chapter 8

General discussion and conclusions

8.1. Introduction

Following the objectives of this PhD study, the thesis is formed by three parts: 1) laboratory experiments regarding airflow characteristics in pig house with partial pit ventilation system (PPV); 2) field experiments regarding gaseous emissions from pig house with PPV; and 3) modelling airflow and gas dispersion inside pig house using CFD techniques.

The first part was conducted in the laboratory condition. Airflow characteristics in an experimental ventilation chamber of pig production unit with a PPV system were investigated (Chapter 2). Due to the difficulties in measurements near the animal occupied zone (AOZ) and zone under the slatted floor in filed conditions, scale model studies are desired in the investigations of airflow characteristics. It has been demonstrated that the air movements inside the animal building highly influence the dispersion of airborne pollutants (Morsing, Strom, Zhang & Kai, 2008). Information of the airflow characteristics in animal house, especially near the pollutant source zone, is useful for understanding the pollutants transport mechanisms and further applications. In this thesis, three primary factors influencing the airflow characteristics in a pig house with PPV system are investigated: 1) types of air inlets (Pohl & Hellickson, 1978), 2) ventilation rate (Strom, Zhang & Morsing, 2002) including inlet air-jet momentum (Zhang et al., 2008), and 3) floor types (Aarnink, Swierstra, Van Den Berg & Speelman, 1997; Morsing et al., 2008).

The second part was experiments in real conditions. This part mainly discussed the applications of the PPV system in field experiments (Chapter 3, 4, 5). Although experimental condition can be well controlled in laboratory scale model studies, there were still challenges to reveal the real state due to the complex behaviour of gaseous release from pig production. In addition, before application of PPV systems in large scale commercial farms, it is crucial to have test, evaluation, and validation in practical conditions first. In this thesis, two trials of experiments including both summer and winter periods were carried out in an experimental fattening pig production house with PPV systems. Concentrations and emissions of ammonia and greenhouse gases were measured continuously and analysed. Effects of different ventilation configurations and seasonal variations on indoor air quality and gaseous emissions were investigated (Chapter 3, 4, 5).

The third part was numerical modelling of airflow and dispersion in the pig house. Computational fluid dynamics (CFD) can effectively model airflow in both spatial and temporal fields, and it was proved the potential to model livestock buildings and can provide concrete flow information. With the rapid development of CFD, numerical studies on the airflow and pollutants dispersion in agricultural buildings have become more and more popular. In this thesis, the feasibility of Reynolds-averaged Navier-Stokes (RANS) turbulences models predicting airflow and dispersion inside a pig model with PPV system was studied (Chapter 6). When conducting numerical simulations, a technical issue on simplifying the slatted floor in geometry should be solved before simulations of full scale building. Thus, at the end of this thesis, the uncertainty of modelling slatted floor as porous media was assessed (Chapter 7), which is a pilot work providing some guide for numerical studies in the field conditions in future.

8.2. Airflow characteristics in a pig house with partial pit ventilation system

Ammonia (NH_3), dust and odour released from livestock farming may lead to poor indoor air quality and negative impact to neighbouring environment. Aiming at reduction of emission and optimization of indoor air quality, a concept of partial pit ventilation (PPV) was proposed. The PPV system is using an extra pit air exhaust to extract the most concentrated airborne pollutants directly from the pollution source zone. Two types of ventilation configurations regarding the PPV system have been developed. Both configurations had the same layout of exhaust units: each with a partial pit exhaust and a main room exhaust. The only difference between the two configurations was the type of air inlets. One configuration was equipped with ceiling diffusion/jet air inlet (system-C), while another had wall jet air inlet (system-W).

As mentioned, the air characteristics inside the animal building plays an important role in the dispersion of airborne pollutants (Morsing et al., 2008). However, up until now, limited information is available for a pig house with PPV system. Therefore, the airflow characteristics in a pig house with PPV system combined with the two types of air inlet were investigated in this PhD thesis.

8.2.1. Laboratory study

Scale model studies are popular in the investigations of airflow characteristics since the experiment condition can be easily controlled and model experiment costs much less compared with field experiment.

Laboratory experiments were performed to investigate the influences of two types of air inlet, three types of floor and four levels of ventilation rate on airflow air velocities, turbulence intensities and airflow patterns near the floor region and air exchange rate between room and pit spaces. Generally, increased ventilation rate resulted in higher air velocities either downward or upward at near-floor region. Much higher air velocities and lower turbulence intensities occurred in system-W than in system-C. There was no significant difference in Ti above the floor among the four levels of ventilation rate. Increasing the floor opening ratio enhanced the air exchange rate between room and pit spaces.

In system-W, airflow was driven downward near the far end sidewall and moved upward near the sidewall where wall inlet installed. A similar tendency for Ti changes along the floor length was occurred among all the four ventilation rates under each floor type in system-W. A big dominant return flow was found in system-W. The inlet air injected from wall-jet opening reached the ceiling first and continued to the far end wall. On reaching the floor it roughly split into two: a primary return airflow above the floor and another penetrating flow into the pit.

In system-C, airflow at most part of the floor region moved downward. Higher vertical air velocities were observed at locations near the sidewall with exhausts. There was no clear tendency for Ti changes along the floor length among four ventilation rates, and no clear big flow pattern was observed in system-C. The supply air from diffusion ceiling inlet dropped down slowly and flow to the exhausts on sidewall. There were many small turbulence vortices in the chamber.

Results for ammonia emission from the field study regarding PPV together with different air inlets can be comprehensively explained by using the results of this study.

8.2.2. Field study

Due to the difficulties in measuring detailed airflow characteristics in a pig room with living pigs, only smoke tests were conducted to reveal the airflow patterns inside the building.

In system-W, fresh air from wall-jet inlets reached the ceiling first and travelled some distance, and then started to drop. There was a large return flow near the animal occupied zone. These air flow patterns agreed with the free jet drop model developed by Zhang, Morsing, and Strom (1996). Normally, supplied air dropped down slowly and smoothly through diffusion ceiling in system-C. When the ceiling-jet inlets were open in summer, high speed fresh air was injected into the drain floor area. There was almost no air went into the room through diffusion ceiling at that situation. Small proportion of short circuiting of incoming air to room exhaust openings occurred in both systems. The short circuiting of incoming air could dilute the gaseous concentration in room exhaust, and made the concentration value lower in room exhaust air than in animal occupied zone (AOZ). It had no influence on ammonia emission from the pig room since emission subjected to the mass conservation law.

8.3. Gas emissions from a fattening pig house with partial pit ventilation system

Intensive pig production is a primary source of gaseous emissions (Cabaraux et al., 2009; Hutchings, Sommer, Andersen & Asman, 2001; Philippe et al., 2011). Emissions of NH_3 to the atmosphere are implicated in soil acidification and eutrophication of aquatic ecosystems (Krupa, 2003). Besides, NH_3 is a well-known toxic gas, which has potential health hazards to both human beings and animals inside the animal house (Banhazi, Seedorf, Rutley & Pitchford, 2008; Donham, 1991). Emissions of greenhouse gases (GHG), including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), are connected with global warming and climate change. Therefore, methods for mitigating NH_3 and GHG emissions are eagerly required (United Nations Economic Commission for Europe, 2013).

To control and reduce gaseous pollution from livestock production, the partial pit ventilation (PPV) system with an extra pit exhaust under slatted floor has been applied in practical conditions. Employing a PPV system can remove the concentrated gases from the pit space above the manure surface before convection airflow and turbulences transfer the gases up to the room space, and significantly improve indoor air quality (Saha, Zhang, Kai & Bjerg, 2010). Consequently, both working environment and animal welfare are improved. In this PhD study, PPV combined with diffusion ceiling and ceiling jet air inlets (system-C), and wall-jet air inlet (system-W) under summer and winter conditions was investigated in an experimental fattening pig production house.

8.3.1. Gaseous release from pig house with PPV

In livestock building, NH_3 emissions were principally generated from the microbial degradation of urea by the enzyme urease in faeces (Muck & Steenhuis, 1981). The NH_3 release process is closely related to air velocity at the manure surface, area of manure surface, air and manure temperatures, pH change in the surface manure, the manure production by animals, and etc. (J. Ni, 1999). With fattening pigs kept under PPV system, average emissions of 4.67 and 6.55 g NH_3 d^{-1} pig^{-1} were measured from system-C and system-W, respectively, during summer. The comparable values for winter period were 4.57 and 4.59 g NH_3 d^{-1} pig^{-1} from system-C and system-W, respectively.

N_2O is produced during incomplete nitrification and denitrification processes which need both aerobic and anaerobic conditions (Monteny, Bannink & Chadwick, 2006). As neither of the two conditions occurred in the slurry under the slatted floor (Cabaraux et al., 2009), negligible amount of N_2O was observed in a pig house with PPV system.

CH_4 originates from enteric fermentation by pigs and anaerobic degradation of organic matter in manure (Cabaraux et al., 2009; Hellmann, Zelles, Palojärvi & Bai, 1997). In this study, average CH_4 emissions were 1.15 to 1.55 g d^{-1} pig^{-1} during summer. The values for winter period were 4.47 to 4.79 g CH_4 d^{-1} pig^{-1}. Two sharp decreases of CH_4 emission occurred during the slurry emptying processes.

Normally, there are two main source of CO_2 production in a piggery without combustible heating: animal respiration and manure release *(J. Q. Ni, Hendriks, Coenegrachts & Vinckier, 1999)*. In the pig house with PPV system, the measured CO_2 productions ranged from 30.3 to 99 g h^{-1} pig^{-1} for pigs weighing from 30.1 to 111.5 kg. Comparing the last days of fattening period with and without pigs, the quantity of CO_2 released from manure contributed 2.3-3.4% of the total CO_2 production.

8.3.2. Effects of different types of air inlets on gaseous emissions from pig house with PPV

The ventilation system of animal houses has significant influence on local thermal conditions and gaseous release (Barber & Ogilvie, 1982; Zhang et al., 1996). Meanwhile, the dispersion of gaseous contaminants is mostly affected by airflow inside the livestock building (Zhang & Strom, 1999).

In current study, the two different designed air inlets induced two different ways of air supply into rooms and consequently, two kinds of airflow conditions. More air was required for system-C than for system-W. Higher ventilation rate could result in lower ammonia concentrations due to air dilution. Therefore, gas concentrations were always higher in room air and lower in pit air for system-C than for system-W.

Despite gas dilution, gas concentration is principally determined by gas release which is affected by airflow patterns and air exchange rates between room and pit spaces (Ye, Saha, et al., 2009; Ye, Zhang, et al., 2009). In system-W, the injected air *via* wall-jet formed a full return flow in the room, which generated higher air speed and turbulence near the slatted floor comparing to that in system-C (Bjerg, Zhang & Kai, 2008a, 2011). The downward air at one end of the pens could easily penetrate the pit headspace through the openings of slatted floor, resulting in high air exchange between room and pit air (Morsing et al., 2008; Zhang et al., 2008). Mass transportation of gaseous contaminants was driven in the exchange air as well.

8.3.3. Seasonal influence on gaseous emissions from pig house with PPV

Room ventilation requirement increased as outdoor temperature was high. Larger amount of fresh air was required in summer than in winter, which resulted in bigger inlet air momentum (mass × velocity) in summer than in winter. The higher inlet air momentum was likely to increase air exchange rate between room and pit space and also increase air speed on the slurry surface. Higher mass transportation including NH_3 and GHG was also driven in the exchange air. Consequently, higher emissions were found in the fattening period in summer than in winter. This is agree with previous study which concluded that higher ventilation rate induce higher gaseous emissions (Aarnink & Wagemans, 1997; Arogo, Zhang, Riskowski, Christianson & Day, 1999; Saha et al., 2010; Ye, Zhang, Li, Strøm & Dahl, 2008; Zhang et al., 2008). On the other hand, due to effect of air dilution, the gas concentrations were generally lower in summer than in winter.

8.3.4. Comparison with conventional fattening pig house

Indoor air concentration of NH_3 is a key parameter for determining air quality in pig house as it can significantly affect the health of both human beings and animals inside the building (Saha et al., 2010; Ye et al., 2008; Zhang et al., 2005). In current study, the average indoor NH_3 concentrations were only 2.1-3.4 ppm in summer and 4.2-4.3 ppm in winter, which were much lower than those from fattening pig rooms using conventional ventilation system (Groot Koerkamp et al., 1998). The remarkable improvement in indoor air quality was mainly caused by the negative pressure in the pit headspace with PPV, which could prevent the upward air exchange through the slots, hence lowered ammonia concentrations in the pig rooms (Aarnink & Wagemans, 1997; Gustafsson, 1987). Animal welfare was improved as better indoor quality was achieved in the animal house with PPV system.

Approximately half of the ammonia emission was extracted via pit exhaust, which only accounted for 10% of the maximum ventilation rate. If applying an effective air purification system, a significant reduction of ammonia emission can be achieved.

8.4. Modelling of pig house using CFD methods

Information on the airflow characteristics and contaminants distribution in pig house is useful for understanding the transport mechanism in pig house and further application. However, detailed measurements both in laboratory and field conditions are very expensive and often difficult. As an alternative approach, Computational fluid dynamics (CFD) is a useful and reliable tool to predict airflow and dispersion across wide research areas. It becomes popular to study airflow and dispersion in animal houses using CFD techniques.

8.4.1. Assessment of RANS models to predict airflow and dispersion from pig house with PPV

Most CFD models have been successfully used for simulating airflow and dispersion inside confined spaces (Lee et al., 2013; Norton, Sun, Grant, Fallon & Dodd, 2007). However, CFD need to be evaluated before it can be used as a practical engineering tool for predictions in buildings. The selection of a turbulence model greatly influences the prediction accuracy of airflow and dispersion in buildings because it strongly affects the reproduction of the flow structure in buildings (Liu, Niu & Kwok, 2013).

In this study, we aim to evaluate the performance of five widely used turbulence models, the standard k-ε (SKE), the renormalization group k-ε model (RNG), the realizable k-ε model (RKE), the standard k-ω model (SKW) and the shear stress transport k-ω model (SST-KW) on predicting airflow velocities and concentrations in a full scale climate chamber of pig house with a PPV system. The turbulence models were evaluated by comparing the numerical results with experimental data. Results show that the overall air velocities both on horizontal and vertical directions and concentration profile along the length of chamber can be revealed by numerical results. The RNG k-ε was found to be the best in predicting airflow and dispersion in a pig model with PPV system among the five investigated RANS turbulence models.

8.4.2. Simplification of modelling slatted floor

The slatted floor system is common in pig and cattle housing. In a livestock building with a slatted floor system, pollutants like ammonia and odours are mostly emitted from the zone near the slatted floor, either the floor surface or the slurry pit under the floor (Saha et al., 2010; Ye et al., 2008). The boundary layer around the slatted floors governed the air exchange between pit and room space which further affect the airborne contaminants dispersion. Thus, the accuracy of simulating slatted floor determines the accuracy of gas dispersion modelling.

In practical livestock building, the slot width is up to 0.02 m while the building dimension can be several thousand times larger. The big size difference between slot width and building dimensions including the ventilation openings prevents a direct modelling of the geometrical details for a full scale livestock building. Porous media was thus introduced to tackle this limitation in modelling slatted floor (Bjerg et al., 2008a; Bjerg, Zhang & Kai, 2008b; Sun, Keener, Deng & Michel, 2004; Wu, Zhai, Zhang & Nielsen, 2012). A simplification model using porous media to represent a scaled slatted floor was developed. To assess the feasibility of this simplification, the proposed porous media model (SP) was compared with the direct geometry model (SD). To validate the numerical modelling, a 1:8 scale pit model was constructed in a wind tunnel. The turbulence model of standard k-ε was adopted.

The results showed that the porous media model was able to estimate the air velocities but not the turbulent kinetic energy. Both models predicted rotating flows under the slatted floor. A clear vertical air motion above the slatted floor was found for SP results but no such trend for SD results. The mechanism of the pollutant transportation, including the process of pollutant escaping from the pit and retention time of pollutant inside the pit headspace, was found to be inconsistent for SD and SP models. For SD, the dominant removal mechanism of transporting pollutants from the headspace to the free stream was mean flow transportation whereas it was turbulent flow transportation in SP. Higher emission rate and shorter retention time of pollutant in the headspace was obtained by using SP compared to SD. In general, though the porous media approach cannot reveal the pollutant transport mechanism, it can predict the velocity magnitude. In addition, it was found that the orientation of slats to stream flow direction plays an important role on airflow pattern and pollutant distribution inside the pit headspace.

8.5. Perspectives

This thesis mainly studies the partial pit ventilation (PPV) system through laboratory and filed experiments as well as numerical simulations. Due to time limit, the initial objectives are fulfilled with certain degree, which is discussed below. The discussion can serve for improving future studies on precision zone ventilation system in livestock buildings.

- The PPV as the precision exhaust ventilation from the pollution source zone is only a part of the precision zone ventilation which also consists of direct air supply to the AOZ in animal house and other settings. The studies on direct air supply to AOZ are expected in future study.
- Thermal conditions inside a pig house with PPV system are not included in this thesis. However, it is crucial for the airflow and dispersion inside the building, especially for the pig house with diffusion ceiling inlet where heat buoyant drive the primary airflow pattern inside. It is expected in future studies.
- In this PhD thesis, the field experiments were done in an experimental facility with only 64 pigs in summer and winter conditions. To further evaluate the system performance and generalise emission factors for the partial pit ventilation system, more trials in varied production scales, locations and seasons are needed.
- Effects of slurry depth on ammonia emission from pit exhaust and effect of ventilation requirement on ammonia emission from room exhaust were found in current study. However, systematic study on these effects needs to be done in the perspective work.
- Detailed air movements in real pig production unit should be investigated using CFD techniques.
- Porous media as a simplification method for modelling needs improvement in future studies. Determination of resistance coefficients and factors as well as correction of mass diffusion in the porous zone needs to be further investigated in the perspective work.

8.6. General conclusions

The following general conclusions were drawn from this thesis:

- In an experimental chamber equipped with PPV system, air velocities, turbulence intensities and airflow patterns near the floor region and air exchange rate between room and pit spaces were affected by different ventilation rates, air inlet types and floor types. Higher ventilation rate resulted in higher near-floor air velocity and higher air exchange rate in the pit. Much higher air velocities and lower turbulence intensities were observed in system-W than in system-C. A big dominant return flow was found in system-W, while small turbulent flows were found in system-C. Increasing the floor opening ratio enhanced the air exchange rate in the pit. Results for ammonia emission from a field study regarding PPV combined with two different air inlets can be comprehensively explained by using the results of this study.

- In a pig house equipped with PPV system, ammonia concentration and emission had been always lower in system-C than in system-W during the fattening period ($p < 0.001$), although the latter required less ventilation rate. The gap of ammonia concentration difference between system-C and system-W enlarged in the later stage. Higher room ventilation rate led to smaller difference of ammonia concentration in room air. Slurry depth played a positive effect on the ammonia emission from pit exhaust. There was no significant difference in the pigs' activity between the two PPV systems.
- The total CO_2 production from pig house increased proportionally as the pigs grew. From the data of the last days of fattening period, the quantity of CO_2 released from manure consisted 3.4 % and 2.3 % of the total CO_2 production in system-C and system-W, respectively. The higher pit ventilation rate resulted in higher CO_2 concentration in pit exhaust air and higher emission rate via pit exhaust, but had limited influence on the total emission rate (*via* room + pit exhaust). With a fixed pit ventilation rate, higher room ventilation rate resulted in lower CO_2 concentration in room exhaust air and higher room and total emission rate. The diurnal variations in CO_2 production were mainly influenced by animal activity, which had a diurnal pattern with a narrow peak in the morning and broad peak in the afternoon. The average CO_2 production was 72.7 g h^{-1} pig^{-1} or 0.206 m^3 h^{-1} hpu^{-1}, which was close to previous studies. The CO_2 production model developed in this study produced similar values to the CIGR model for a pig under 80 kg and the Ni's TCER model for a pig above 60 kg.
- On average, the indoor concentrations were maintained 2.1-3.4 ppm for NH_3, 0.4-0.6 ppm for CH_4, and 800-966 ppm for CO_2 in summer; and 4.2-4.3 ppm for NH_3, 5.0-5.6 ppm for CH_4, and 1491-1542 ppm for CO_2 in winter. There were almost no N_2O releases in current set-up with slatted floor and pit ventilation under the floor. Approximately half of the whole NH_3 emission (47-63%) was extracted from pit exhausts. The air purification system for mitigating pollutants from pig house became practical as only treating10% of the exhausted air. The PPV plus air purification system can be an efficient mitigation technique for reducing gaseous pollution from pig production. Gas emissions of fattening period were mainly influenced by the different air-inlets and seasonal times. The two types of PPV systems (system-C and system-W) resulted in two different kinds of airflow characteristics, which further affected the gaseous release process. More fresh air was required for system-C than for system-W to keep a same setting indoor temperature. Lower gases concentrations were observed in system-C than in system-W during summer. During winter, gases concentrations were higher in room air and lower in pit air for system-C than for system-W. Due to smaller air dilution rate, the gas concentrations in room air were higher during winter

than during summer. The daily mean NH_3 emissions were lower, while the daily mean CH_4 and CO_2 emissions were higher, in winter than in summer.

- The performance of the SKE, RNG, RKE, SKW and SST-KW turbulence models was examined for simulating the airflow and gas dispersion in an experimental ventilation chamber of pig house with partial pit ventilation (PPV) system. Through comparisons between experiments and simulations, the overall air velocities both on horizontal and vertical directions and concentration profile along the length of chamber can be revealed by numerical results. Among the five investigated RANS turbulence models, the RNG k-ε was found to be the best in predicting airflow and dispersion in a pig model with PPV system.
- To simulate the slatted floor was investigated, two numerical approaches were proposed: one applied direct geometry model for the slatted floor (SD) and another used porous media model (SP). The SP approach yields predictions comparable to the SD approach on air velocities in the pit headspace. The results of velocity from both approaches can be well validated by measurement, especially on the upwind side. The turbulent kinetic energy cannot be well predicted for most locations with the SP model. An anticlockwise-rotating flow in the cavity was observed by both the SD and SP model. There is a small shift of vortex-centre between two models. A clear vertical air motion in the tunnel space above the slatted floor was found for the SP results, but no such trend for the SD results. Higher concentration of NH_3 distributed on the downwind side for both approaches. There were significant differences between the results from the two approaches in relation to the process of pollutant dispersion from the pit headspace. For SD, the dominant removal mechanism for transporting pollutants from the headspace to the free stream was mean flow transportation whereas it was turbulent flow transportation in SP. The total mass of NH_3 in the pit headspace calculated by the SD and SP models was close to each other. Pollutants with higher emission rate and shorter retention time in the pit headspace were observed when using SP compared to using SD. The orientation of slats in relation to the stream flow direction plays an important role for airflow pattern and pollutant distribution inside the pit headspace.

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