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REVIEW

Study on Forced Ventilation System of a Piglet House

In-Bok LEE[1], Byeong-Ki YOU[1], Chang-Ho KANG[1], Jong-Gil JEUN[1], Gyeong-Won KIM[1], Si-Heung SUNG[2] and Sadanori SASE[3]*

[1] Bio-Production Fundamental Engineering Division, National Institute of Agricultural Engineering (Suwon, Gyeonggi 441–100, Korea)
[2] KonKuk University (Chungju, Chungbook 380–701, Korea)
[3] Department of Agricultural Environment Engineering, National Institute for Rural Engineering (Tsukuba, Ibaraki 305–8609, Japan)

Abstract

The objective of this study was, using the data of field experiment and visualization of internal airflow, to clearly understand forced ventilation of a piglet house with perforated ceiling which was very popular in Korea. This study was conducted at a commercial piglet house to investigate the performance of the forced ventilation and determine the effect of the ventilation system on internal airflow, air temperature, humidity, dust, and gas in the piglet house. The internal airflow patterns were studied with the help of computational fluid dynamics (CFD). Comparing the recommended maximum ventilation rate and measured ventilation rate, the ventilation system of the piglet house was 16% overestimated. The air temperature measured at 0.8 m from the floor in a compartment of the piglet house was always higher than the setting temperature while relative humidity, dust, and ammonia gas were controlled pretty well during data collection. Compared to the measured air velocities at piglet location in the compartment, the CFD computed results showed 10–18% error. The CFD computed results without piglets showed that the maximum air velocities at piglet location were 0.06, 0.55, and 0.95 m/s, respectively for 5, 50, and 100% of ventilation settings. Observing the dilution of internal relative humidity of the time-dependent CFD model, very poor environmental conditions were found at both end wall areas compared to the other areas of the compartment.

Discipline: Agricultural facilities
Additional key words: computational fluid dynamics, perforated ceiling, piglet house

Introduction

Piglets in compartments are mainly stressed by climatic factors and non-climate factors. The main climate factors are air temperature, humidity, air speed, gas, dust, and radiative environment, and the typical non-climatic factor is stocking density. While the non-climate factors can be artificially controlled, most of the climate factors strongly depend on ventilation. Successful piglet houses strongly depend on optimization of a ventilation system that matches the specific requirements of the piglets at a given stage of production as well as local weather conditions. Failure to understand the key role of ventilation may create serious problems in practice, in relation to control of the thermal, dust, and odor environments. Especially, for piglets, the emphasis must be on accurate and stable temperature control to prevent stress and deficiencies in performance[7].

In Korea, it is very cold with humidity in the winter while very hot with high humidity in the summer causing seasonally very serious stress on piglets. However, there is no traditional structural design for livestock housing optimum for the Korean climate while most livestock houses have been copied from Europe. There is no uniform design for livestock housing in any single village because farmers design their livestock housing by themselves according to their own experiences. It has been

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*Corresponding author: fax +81–29–838–7609; e-mail sase@nkk.affrc.go.jp
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indicated that there are not currently satisfactory structural designs available in the market. Accordingly, it is very urgent to find designs for heating, cooling, and ventilation systems of livestock housing optimum for the Korean climate. However, only little information and data have been available on the ventilation system design of forced ventilation in piglet houses because of difficulty in conducting field experiments as well as approaching livestock houses due to disease control measures. While the study of ventilation and structural design by the aerodynamic approach has been mimicked so far in Korea, the best way to effectively understand ventilation efficiency is the visualization of airflow patterns. The aerodynamic approach can be effectively used to design livestock houses for each regional climate as well as livestock growth level.

The objective of the study was, using the data of field experiment and visualization of internal airflow, to clearly understand forced ventilation in a piglet house with perforated ceiling which was very popular in Korea. Later, the data will be used to find the mutually optimized ventilation system for piglet houses. This study was conducted at a commercial piglet house to investigate the performance of the current forced ventilation and determine the effect of the ventilation system on internal airflow, air temperature, humidity, dust, and ammonia gas in the piglet house. The internal airflow patterns were studied with the help of computational fluid dynamics (CFD). A CFD model of the piglet house was programmed with Fluent version 5.5[3], and a time-dependent three-dimensional model was developed. The accuracy of the model was also examined using field experiment data.

Literature review

Health and Safety Executive[4] and Wathes & Charles[12] explained the ventilation requirement for pigs. The maximum requirement is the amount of air necessary to prevent the building from overheating due to metabolic heat. This dictates the capacity of a ventilation system. The minimum ventilation requirement is the amount of air required to provide oxygen and to remove carbon dioxide, ammonia, dust, and other excretory and microbiological by-products. Typical standards are carbon dioxide kept below 0.3% and ammonia kept below 20 ppm. For pigs, the typical minimum and maximum ventilation rate requirements are 2.1×10^{-4} $kg^{0.67}m^3/s$ and 2.1×10^{-3} $kg^{0.67}m^3/s$, respectively. They also indicated that the effective temperature of the pig location decreased 2ºC when the adjacent air speed increased from 0.15 to 0.30 m/s. Dust control is very important for the livestock environment because dust with potentially harmful compounds such as allergic agents, infectious microorganisms, enzymes and toxic gases undoubtedly worsens the indoor air quality and contributes to respiratory health problems in both animals and people.

Choiniere et al.[1] conducted an experiment at an early weaning nursery house to investigate relative humidity, air temperature, NH_3, and CO_2 concentrations for two ventilation systems: pit and wall mounted fan ventilation. The results indicated that there was no noticeable difference in terms of air quality in the nursery between the two ventilation systems for the same ventilation rates. The period of data collection was for 7 weeks after newborn piglets started their life. The maximum ammonia concentration measured at the compartment was 7 ppm during the data collection. Korthals et al.[7] monitored tympanic temperatures and feeding behaviors for growing ad-lib-fed swine exposed for 12 days to increases of 4, 7, or 10ºC above a base environmental temperature of 23ºC constant conditions or to an increase of 7ºC above 23 ± 5ºC cyclic conditions. There was a significant reduction in number of meals, time spent eating and feed intake for the day after compared to the day before the imposition of heat stress.

A two-dimensional computational analysis of ceiling inlet ventilation system for a hog nursery was developed by Khankari et al.[6]. The presence of animals was simulated by creating an obstruction in the airflow with constant body temperature (38ºC). The effects of several design and operating parameters including location and capacity of gas heaters, winter ventilation rates, and ambient air temperatures were evaluated on the distribution of natural convection airflow, air temperature, and sensible heat losses from the animals. In addition, summer ventilation conditions and various systems management strategies were also studied. This analysis indicated keeping only one ceiling inlet (located far from the exhaust fan) open, helped animals to conserve more heat. In all the situations, animals directly under the incoming air jets lose more heat than those at other locations in the nursery.

Lee et al.[9] explained the aerodynamic approach for the design of heating, cooling, and ventilation systems in agricultural buildings. The main tools of the aerodynamic approach were CFD as well as wind tunnel and particle image velocimetry (PIV) system. They clearly explained the difficulty of conducting field experiments for ventilation study. For studying natural ventilation efficiency, it is very difficult to create fairly identical and stable boundary conditions in field experiments, due to unstable and unpredictable weather conditions. Measuring air velocities and overall natural ventilation rates also requires extensive instrumentation and high measurement accuracy. It is also very difficult to approach livestock houses due to disease control measures. Reichrath & Davies[10] also presented a comprehensive review of the state-of-the-art in the application of CFD for modeling the interaction between the internal climate of agricultural buildings with external weather conditions and environmental control settings. They insisted that CFD is now a mature engineering design tool and is increasingly being utilized in various agricultural studies.

Launder & Spalding[8], Choudhury[2], and Fluent Inc.[3] presented detailed information on turbulence numerical models available for CFD models. The RNG k-ε model was derived from the instantaneous Navior-Stokes equations, using a mathematical and statistical technique called "renormalization group (RNG)" method. Choudhury[2] and Fluent Inc.[3] insisted that the RNG k-ε model is more accurate and reliable for a wider class of flows than the other turbulence models. Wu & Gebremedhin[13] also evaluated turbulence models for predicting flow fields in a multi-occupant ventilated space. Five different turbulence models were evaluated in order to establish the most appropriate model for ventilated spaces in animal housing. Based on convergence and stability criteria, the RNG k-ε model was found to be the most appropriate model for the application considered in this study. Fluent Inc.[3] also indicated limitations of development of the porous media in CFD models. It showed that the porous media model is nothing more than an added momentum sink in the governing momentum equations. Sun et al.[11] also developed a three-dimensional CFD model to predict the airflow pattern and ammonia distribution for summer conditions within an experimental High-Rise™ Hog Building (HRHB).

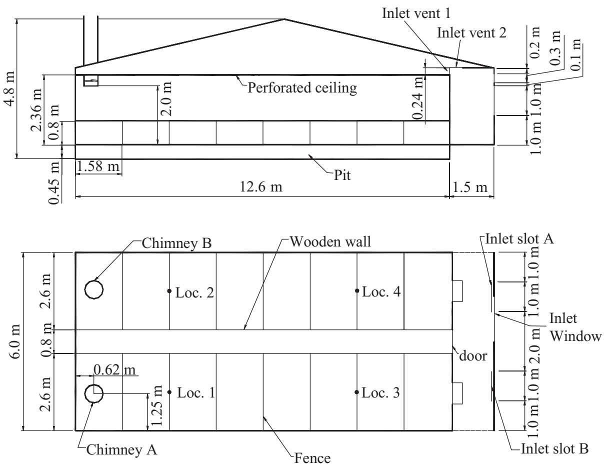

Fig. 1. Schematic diagram of an experimental commercial piglet house of Darby Pig Breeding (DPB) Co., Ltd. located at KyoungKi-Province in Korea

Materials and methods

1. Piglet house configuration and measurements

A compartment of a commercial piglet house with 16 fully slotted pens of 14 piglets in each was used for this study. The fattening period lasted about 7 weeks after the 3-week-old piglets started their new life at the compartment. It was built at Yeoulmok Farm of Darby Pig Breeding (DBP) Co., Ltd., near AnSung-City, KyoungKi-Province (37º 10'N, 127º 40'W, elevation 340 m) in Korea. The size of the piglet house compartment was W 6.0 × D 12.6 × H 2.4 m with perforated ceiling and two duct ventilators as shown in Fig. 1 and 2. The roof cover and outside wall of the piglet house were 80 and 100 mm thickness of sandwich panel, respectively

(1) Inlet vents 1 and 2

(2) Inlet slots and window

Fig. 2. Inlet vents, inlet slots, and window at corridor of the experimental commercial piglet house

while the ceiling was single-layered metal panel. The diameter of each hole of the perforated ceiling was 0.01 m and the distance between adjacent holes was 0.25 m resulting in about 1% of overall porosity. The perforated ceiling was designed to prevent the cold outside air from directly reaching piglets. As shown in Fig. 1, the variable fans (ϕ 0.45 m) in two chimneys (ϕ 0.47 m) were controlled by a proportional controller.

As shown in Fig. 2, outside air came into the piglet building through windows (1.0 × 1.0 m) and inlet slots (0.3 × 1.0 m) at the corridor. Air was taken from the corridor through the inlet vents. The sizes of the inlet vents 1 and 2 were 0.25 × 1.0 m and 0.4 × 1.4 m, respectively. The workers at the building usually kept 1/4 of inlet vent 1 open and closed the window during the cold season to prevent too much cold air from coming over the ceiling. The inlet vent 2 was additionally made 2 years ago because the workers believed it would help fan operation as well as increase the ventilation rate during high ventilation. Internal air was expelled through two chimney ventilators. The main heat sources in the compartment were pipe heating and 16 heating lamps (300 W) while the slotted floor greatly reduced the labor to remove manure.

Twenty-five thermocouples were evenly installed at two levels in the compartment and they were connected to a datalogger (Series 3000 Datalogger, Westronics Inc., USA). Fifteen thermocouples were installed along the room at 1.8 m height (3 by 5) while the rest of the sensors were installed at 0.8 m height, just above the piglet location. Eight humidity sensors (Thermo Recorder TR-72S, T&D Corp., Japan) were also installed evenly at 0.8 m height. In the compartment, the thermocouple could not be installed at the aisle at a lower level because it would prevent worker's easy approach.

2. Computational fluid dynamics

The CFD technique numerically solves the Reynolds-averaged form of the Navier-Stokes equations within each cell in a domain[3,8]. The governing equations were discretized on a curvilinear grid to enable computations in complex and irregular geometry. The Reynolds-averaged process considers the instantaneous fluid velocity to be the sum of a mean and a fluctuating component, the turbulence. Since the high-frequency and small scale fluctuations of turbulent flow can not be directly quantified, turbulence numerical modeling relates some or all of the turbulent velocity fluctuations to the mean flow quantities and their gradients.

The RNG k-ε model was derived from the instantaneous Navier-Stokes equations, using a mathematical and statistical technique called "renormalization group (RNG)" method[2]. It is similar in form to the standard k-ε model, but includes the following refinements. First, the RNG k-ε model has an additional term in its ε equation that significantly improves the accuracy for rapidly strained flows. Second, the effect of swirl on turbulence is included in the RNG model, enhancing accuracy for swirling flows. Third, the RNG theory provides an analytical formula for turbulent Prandtl numbers, while the standard k-ε model uses user-specified, constant values. Moreover, while the standard k-ε model is a high-Reynolds-number model, the RNG theory provides an analytically-derived differential formula for effective viscosity that accounts for low-Reynolds-number effects. Effective use of this feature does, however, depend on an appropriate treatment of the near-wall region. These features make the RNG k-ε model more accurate and reliable for a wider class of flows than the standard k-ε model. The analytical derivation results in a model with constants different from those in the standard k-ε model, and additional terms and functions in the transport equations for turbulent kinetic energy, k (m^2/s^2) and turbulent dissipation rate, ε (m^2/s^3).

The RNG k-ε model has a similar form to the standard k-ε model:

$$\rho\frac{Dk}{Dt} = \frac{\partial}{\partial x_i}\left[\alpha_k\mu_{eff}\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon - Y_M \quad (1)$$

$$\rho\frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i}\left[\alpha_\varepsilon\mu_{eff}\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R \quad (2)$$

In these equations, ρ is density (kg/m^3) and G_k represents the generation of turbulent kinetic energy due to the mean velocity gradients ($kg/m{\cdot}s^3$). G_b is the generation of turbulent kinetic energy due to buoyancy ($kg/m{\cdot}s^3$). Y_M represents the contribution of fluctuating dilatation in compressible turbulence to the overall dissipation rate ($kg/m{\cdot}s^3$). α_k and α_ε are the inverse effective Prandtl numbers for k and ε, respectively while μ_{eff} is effective viscosity (m^2/s) and $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are constants. The R term in equation (2) is given by :

$$R = \frac{C_\mu\rho\eta^3(1-\eta/\eta_0)}{1+\beta\eta^3}\frac{\varepsilon^2}{k} \quad (3)$$

where $\eta \equiv Sk/\varepsilon$, $\eta_0 = 4.38$, and $\beta = 0.012$. S is a scalar measure of the deformation tensor based on the magnitude of the vorticity.

3. Experimental procedures

The first experiment was performed from Oct. 11 to Nov. 30, 2001 with piglets in the compartment. The objective of the experiment was to clearly understand the internal environment made by the current ventilation system. The ventilation rate could be set from 0 to 100% while the DBP Company decided that the 100% ventilation setting was appropriate considering piglet number and growth level. The ventilation was set usually at 5–15% during the data collection. A datalogger and personal computer collected all data from the measurements of air temperature and relative humidity in the compartment each hour. While the internal air temperature and humidity were continuously measured, portable sensors were used to intermittently measure dust (Model 8520 DustTrak Aerosol Monitor, TSI Inc., USA), ammonia (AP-400 Precision Gas Detector, Kitagawa Co., Japan), and internal airflow (two-dimensional anemometer, Testo 950, Testo GmbH & Co., Denmark) at the locations of relative humidity sensors. The 1-minute averaged data were collected 5 times each week. For the outdoor climate, the weather data measured at a weather station located very close to the farm were used for this study. Unfortunately, at the 7th week, a fatal disease occurred around the experimental farm, so our research team had to stop the data collection and move out from the farm for disease control.

On Feb. 16–17, 2002, the second experiment was conducted without any piglets in the compartment to investigate the performance of ventilation system components such as fan, perforated ceiling, and inlet vent size. First, the forced ventilation rate was measured at the chimney to find the actual ventilation rate using an anemometer (Testo 400, Testo GmbH & Co., Denmark). It was examined to investigate if the size of the inlet vents made any load on the fan operation. The ventilation rate was automatically controlled according to internal air temperature while farm workers frequently changed the rate manually when, based on experience, they felt dust and gas concentrations were too high in the compartment. The actual ventilation rates were also examined for each ventilation setting. The vertical downward air velocity was measured at just below the ceiling at location 1 through 4 shown in Fig. 1 for each ventilation rate to investigate whether the air uniformly came down through the whole ceiling area. The internal airflow was also measured along the compartment.

The measurement of very low and three-dimensional air velocity was very difficult and expensive in the compartment, so airflow visualization can be a very valuable tool to effectively study the effects of ventilation system design and structural specification on internal air quality. A three-dimensional CFD model was developed to investigate internal airflow distribution without piglets. The RNG k-ε turbulence model was used in this study because it has been known to be more accurate and reliable for a wide class of flows than the other turbulence models[2,3,13]. For the CFD model, the fence was not simulated in the compartment because it was assumed that its effect on internal airflow was negligible. Feed tanks were also ignored. In the CFD model, porous media was not developed for the slotted floor and perforated ceiling because accurate CFD results could not be obtained when the airflow direction was not perpendicular to the porous plate[3]. In the CFD model, considering the locations of inlet vents and chimney ventilators, 30 thin slots were evenly developed as the slotted floor horizontally to the end walls having 50% of porosity. The perforated ceiling was also specified using 30 thin slots making 1% of the overall porosity.

Considering three-dimensional velocity as mean + fluctuating component ($u = \bar{u} + u'$, $v = \bar{v} + v'$, $w = \bar{w} + w'$), the turbulence kinetic energy and turbulent dissipation rate that are the important inlet boundary conditions for the velocity components were calculated[5] as:

$$k = \frac{1}{2}(u'^2 + v'^2 + w'^2) \tag{4}$$

$$\varepsilon = \frac{C_\mu^{3/4} \cdot k^{3/2}}{l},\ l = \min(k \cdot z_n, k \cdot \delta) \tag{5}$$

where

C_μ empirical constant
Z_n vertical distance from ground (m)
δ thickness of turbulence boundary layer (m)
k von Karman constant

The data measured at a compartment on Feb. 16 were used as CFD input data, and there was not any heating during the data collection. All the surface temperatures of the compartment were the same as external air temperature, 6ºC while the exit air velocities at the chimneys A and B were 2.1 and 2.2 m/s, 10.1 and 9.8 m/s, and 13.9 and 14.0 m/s, respectively for 5, 50, 100% of the ventilation settings. For investigating CFD accuracy, measured and computed internal air velocities were compared with each other. The airflow was very unstable and three-dimensional in the compartment, so it was not advisable to compare CFD computed air velocity to the air velocity measured by a two-dimensional anemometer in the compartment. Moreover, the feed tanks and fences might make different internal airflow patterns in the actual case compared to the CFD computed airflow without any simulation of the feed tanks and fences. Fortunately, the CFD results indicated that the airflow was very one-dimensional at the corridor of the compartment. Both 0.8 m wooden walls helped the airflow to be stable. Accordingly, the measured and CFD computed air velocities at 0.3 m from the floor of the center of the compartment were compared with each other according to ventilation rates. And then, using the CFD, internal airflow patterns for each ventilation rate were investigated. Moreover, to fairly study the effect of ventilation system design on internal air exchange, a time dependent simulation was developed. Initially 40% of relative humidity was specified at the internal volume of the compartment while the relative humidity of inlet air was 20%. After starting the time dependent simulation, dilution of relative humidity in the compartment could be fairly observed and then examined, and then some poor ventilation areas developed by the designs of ventilation systems as well as structures could be easily found. The dilution of relative humidity was observed for 1 min in the CFD model.

Results and discussions

The internal air temperature and relative humidity were measured for 43 days from Oct. 11 to Nov. 24, 2001. While the weekly setting temperature decreased from 28 to 21ºC through the 7 weeks shown in Fig. 3, the average internal air temperature measured at 0.8 m from the floor in the compartment was always higher than the setting temperature. Meanwhile, the outside air temperature gradually decreased during the data collection. The main reason was that two temperature sensors connected to the controller were located at 1.3 m from the floor where the air temperature was lower than the piglet location because fresh air came down from the perforated ceiling. Moreover, the workers frequently changed the number and intensity of each heating lamp turned on by considering dust and gas concentrations in the compartment as well as internal air temperature while the maximum and minimum ventilation rates were fixed at 5% and 15%, respectively during the data collection. The average internal air temperature also fluctuated greatly because the internal air thermal conditions and quality were continuously influenced by both the manual and automated operations of the heating and ventilating systems as well as by feeding time and piglet movements. The changing pattern of internal air temperature from the 14th day looks very similar to the change in external air temperature while the maximum range of the spatial distribution in the internal air temperature was 5.3ºC. The

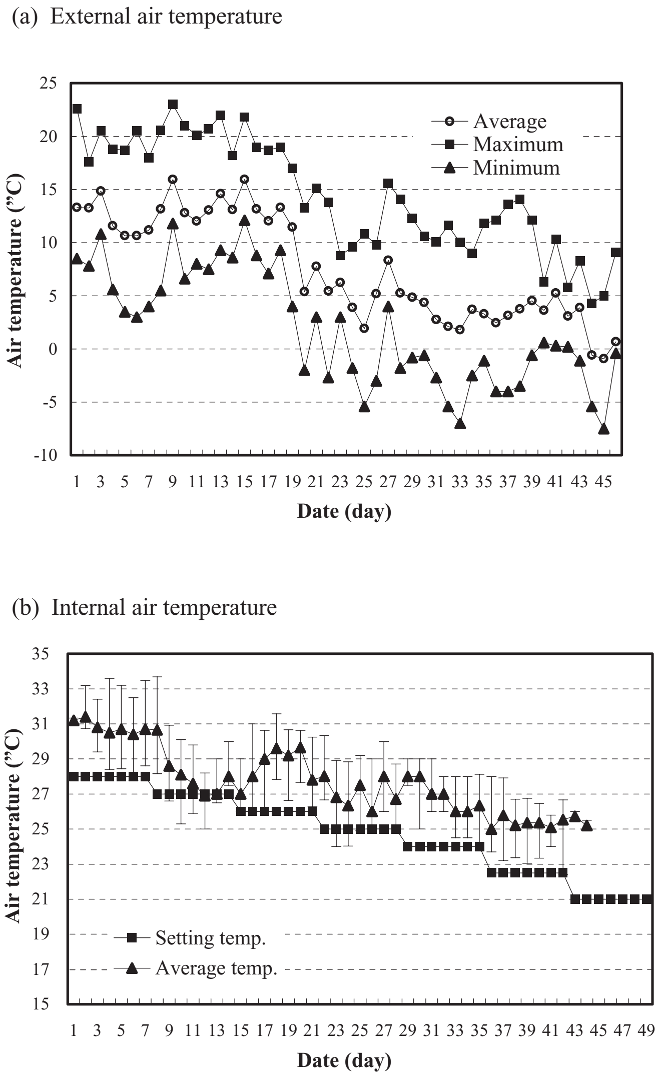

Fig. 3. The external air temperature (a) and internal air temperature (b) measured at 0.8 m from the floor from Oct. 11 to Nov. 30, 2002

range in the internal air temperature was determined from the maximum and minimum air temperatures measured during the data collection. This big range was caused by the lowest air temperature always being measured close to the door because a little cold external air came in through cracks in the door. Moreover, the locations of the temperature sensors were also one of the important factors for the big range in the internal air temperature. Some of the sensors were located close to the heating lamps while others were not. As shown in Fig. 4, when the ventilation rate was generally 5 to 10% on Oct. 12, 2002, the average air temperatures at 0.8 m and 1.8 m were 31.6ºC and 30.0ºC, respectively resulting in a 1.6ºC temperature difference. The overall range in internal temperature of the compartment was 4ºC on Oct. 12,

2002. While the workers rarely entered the compartment, the internal air temperature was higher during daytime than nighttime because of the effect of external air temperature and solar radiation.

Compared to the air temperature, the relative humidity was much more stable for the 43 days showing the range of 50–65%. The maximum and minimum relative humidity outside the piglet house were 97% and 20%, respectively during the data collection. The ventilation rate was normally kept very low (5–15%) during the first experiment to save energy during the cold season making the control of dust, humidity, and gas difficult. However, the dust and ammonia gas concentrations were much lower than that recommended by Health and Safety Executive[4] and Wathes and Charles[12]. The daily average dust concentration greatly increased from the third week as shown in Fig. 5. At the 42nd day, the average dust concentration reached 0.64 mg/m^3 while the dust concentration greatly increased during feeding time. Ammonia gas was also controlled pretty well showing less than 10 ppm during the data collection. The workers regularly sprayed disinfectant water on the wall and floor to keep them clean and control the humidity. However, dust and ammonia concentrations were pretty high around the chimney compared to the other areas. The maximum dust and ammonia concentrations measured at this area were 0.71 mg/m^3 and 10 ppm, respectively at the 42nd day.

As shown in Fig. 6, the effect of inlet vent size on ventilation rate was investigated without piglets to examine if the fan performance was loaded or not according to the inlet vent size. In the figure, the ventilation rate of 0–100% means the ventilation setting of the control system is decided by the rotation number of the exhaust fans. The data were the averaged data of 4 trials of 1-minute. As shown in the figure, the measured volumetric airflow was not linear with the setting percentage. It was likely that the performance of the fans was affected by room size and porosity of the perforated ceiling. The volumetric ventilation rate was seriously loaded with a 25% opening of inlet vent 1 while not greatly affected by additional opening of inlet vent 2. It was impossible to continue the measurement with the 25% opening of inlet vent 1 because of the danger of fan damage. When the ventilation setting was 100%, the measured ventilation rates were 4.69 m^3/s and 4.84 m^3/s, respectively for inlet vent 1 open and inlet vent 1 and 2 open. This indicated that the system was 16% overestimated considering 4.17 m^3/s as the recommended ventilation rate. The recommended value was calculated by Wathes and Charles[12] considering the number of piglets in the compartment and piglet's maximum weight in the piglet house.

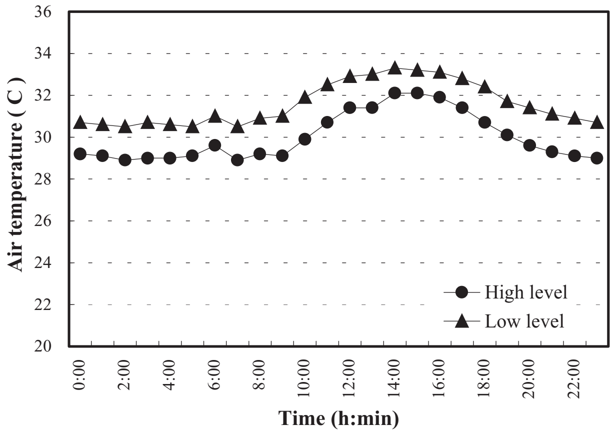

Fig. 4. The change in average internal air temperature measured at 0.8 m (low level) and 1.8 m (high level) on Oct. 12, 2002

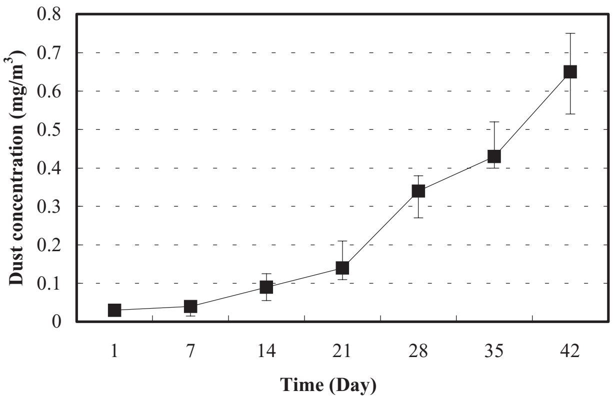

Fig. 5. The change in dust concentration in the compartment of the piglet house from Oct. 11 to Nov. 24, 2002

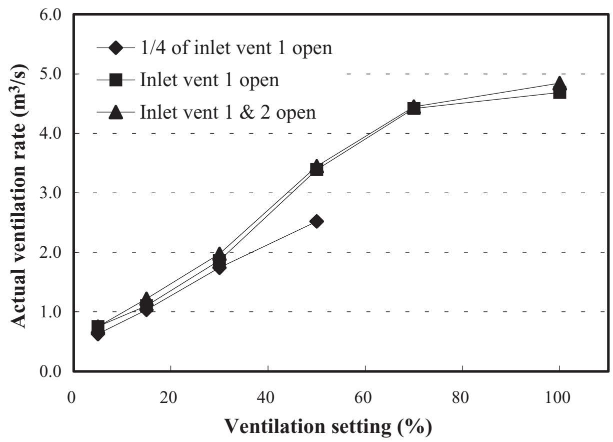

Fig. 6. Airflow rates through the chimney in the piglet house according to the fan ventilation setting

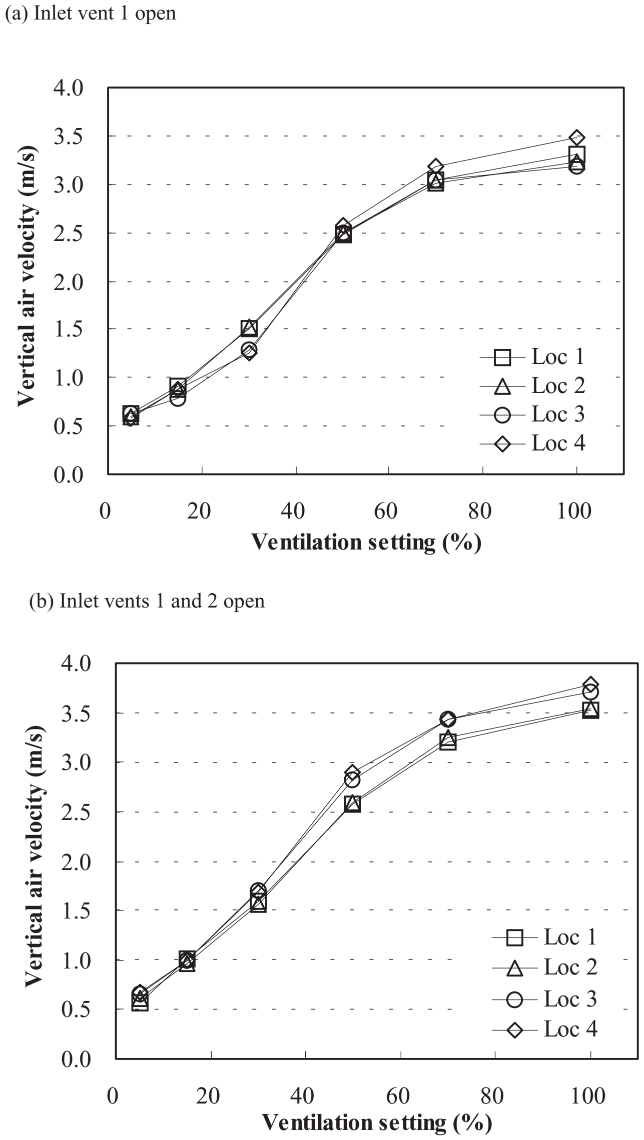

Fig. 7. Vertical downward air velocities measured at the holes of the perforated ceiling for inlet vent 1 open (a) and inlet vents 1 and 2 open (b)

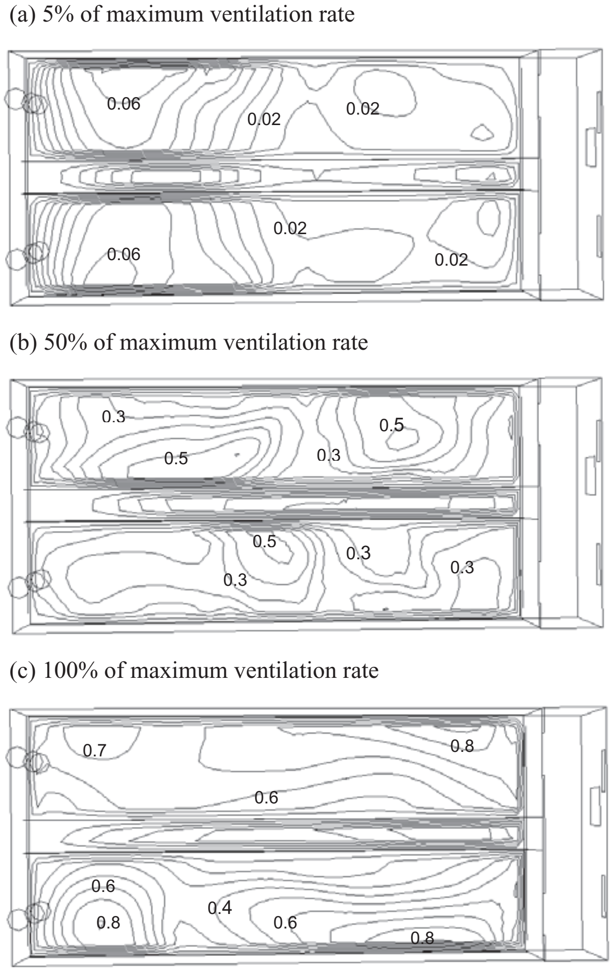

Fig. 8. CFD computed air velocity m/s distribution at 0.3 m from the floor of the compartment for 5% (a), 50% (b), and 100% (c) of the ventilation setting

As shown in Fig. 7, the measured downward air velocities look fairly uniform along the perforated ceiling. This indicated that very uniform air pressure was made above the ceiling resulting in very uniform downward airflow through the whole area of the perforated ceiling. The uniformity is very important to make uniform thermal and air quality distribution in the compartment. Much turbulence or opposite direction airflow against the direction to the chimneys in the compartment could be caused by poor ventilation and structural designs. Then, the environmental conditions will not be greatly improved even with the optimum ventilation rate because of unnecessarily long traveling distances of incoming air before exiting. When the ventilation setting was 100%, the average downward vertical air velocities were 3.30 and 3.64 m/s, respectively for inlet vent 1 open and inlet vent 1 and 2 open.

The comparison of measured and CFD computed air velocities at 0.3 m height of the center of the compartment showed 18% and 10% of positive error, respectively for 50% and 100% of ventilation setting. The CFD computed air velocities were 0.28 and 0.68 m/s, respectively for 50% and 100% of ventilation settings while 0.33 and 0.75 m/s of the CFD computed, respectively. The measured air velocities were the 1-minute average values. The results showed that the error was bigger for the lower ventilation rate. The comparison was not performed for 5% of ventilation setting because the air velocity was too low to measure in the compartment. Fig. 8 shows the CFD computed air velocity distribution at 0.3 m from the floor. It shows that the air velocity was generally very low at the piglet location. The maximum wind velocities were 0.06, 0.55, and 0.95 m/s, respectively for 5, 50, and 100% of ventilation rates. It indicated that this perforated ceiling ventilation system might not be able to make sufficient air velocity at the piglet location during the hot season while Wathes and Charles[12] insisted that certain wind speed was needed at the piglet location to decrease the effective body temperature. Moreover, those wind velocities can be greatly decreased in the case of animals being present in the compartment. The distribution of the wind velocity at the piglet location was not symmetric in the compartment because the fan performance was not identical and the single window at the corridor caused different airflow rates between the left and right inlet vents. Observing the air velocity distribution in the compartment shown in Fig. 8, the location of high air velocity was close to the chimneys when the ventilation rate was low. This was caused by the high air velocity exiting through the chimneys compared to the other areas in the compartment.

Fig. 9 shows the CFD computed relative humidity at the plane bisecting the chimney A when the ventilation rate was 1 internal volume change per minute. The relative humidity of inlet air was 20% while the relative humidity of the internal compartment volume was 40%. As shown in Fig. 9, the internal relative humidity was not completely diluted even after 1 minute, especially at both end wall sides due to the locations of inlet and outlet of the ventilation system. In Fig. 9, the maximum and minimum relative humidity were (a) 20% and 40%, respectively and (b) 20% and 25%, respectively. For the simulation, there was not any continuous generation of heat and mass in the compartment. In the case there were actual piglets continuously generating heat and mass, those areas could be assumed to have very poor environmental conditions. Moreover, the environmental conditions at the piglet location may be worse when the airflow decreases with the existence of piglets. The workers at the farm have already known this fact, so initially they have put stronger piglets at the outer areas while weaker ones have always been located at the center area.

Conclusions

1. The average internal air temperature measured at 0.8 m from the floor, just above the piglet location, in the compartment was always higher than the setting temperature and very unstable because of the location of the temperature sensors connected to the controller and frequent manual operation of ventilation and heating.
2. Dust and ammonia gas were controlled pretty well showing mostly less than 0.7 mg/m^3 and 10 ppm, respectively during the data collection while they were pretty high around the chimney compared to the other areas. The internal relative humidity was kept at 50–65% during the data collection.
3. The measured overall maximum ventilation rate was 4.84 m^3/s. Considering 4.17 m^3/s as the recommended

(a) 30 sec after the beginning of ventilation

(b) 60 sec after the beginning of ventilation

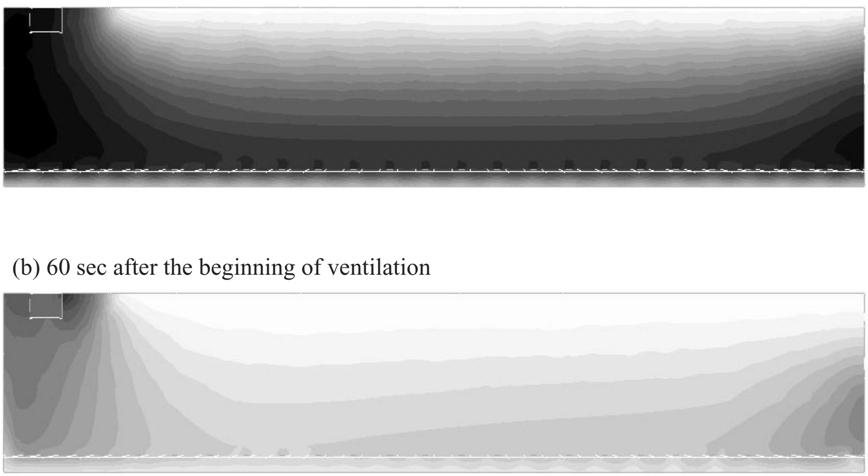

Fig. 9. CFD computed relative humidity at the plane bisecting chimney A
The maximum and minimum relative humidity were (a) 20% and 40%, respectively and (b) 20% and 25%, respectively when the ventilation rate was 1 internal volume change per minute.

maximum ventilation rate, the current system was 16% overestimated.

4. The measured downward air velocities from the ceiling indicated very uniform downward airflow through the whole area of the perforated ceiling.
5. Compared to the internal air velocities measured at 0.3 m from the floor of the center of the compartment, the CFD computed results showed 10–18% error.
6. Without animals in the compartment, the CFD computed maximum wind velocities at piglet location in the compartment were 0.06, 0.55, and 0.95 m/s, respectively for 5, 50, and 100% of ventilation settings.
7. The dilution of internal relative humidity of the CFD model indicated that the internal relative humidity was not completely diluted even with the ventilation rate of 1 internal volume air exchange per minute. Especially, both end wall sides showed very poor environmental conditions compared to the other areas in the compartment due to the locations of inlet and outlet of the ventilation system.
8. While this study was performed during the cold season, another study should be also conducted during the hot season to fairly investigate whether this system was correctly designed for the Korean climate.
9. During this study, it was realized that the CFD simulation could be a valuable tool for analyzing the internal climate factors as well as the designs of heating, cooling, and ventilation systems in greenhouses. This is also a significant benefit for understanding the functionality of the greenhouse structural characteristics with respect to ventilation.

References

1. Choiniere, Y., Marquis, B. & Gingras, G. (1997) Indoor air quality with and/or without pit ventilation in a early weaning pig barn. *In* Proceedings of the fifth international symposium of livestock environment, Minnesota, 2, 866–874.
2. Choudhury, D. (1995) Introduction to the renormalization group method and turbulence modeling. 1993 Technical memorandum TM-107, Fluent Inc., Lebanon, NH.
3. Fluent Inc. (2000) The manual of computational fluid dynamics, Version 5.5, Fluent Inc., Lebanon, NH.
4. Health and Safety Executive (1992) Occupational exposure limits. Environmental hygiene 40/92, HMSO, London, UK.
5. Ishihara, T. & Hibi, K. (2002) Numerical study of turbulent wake flow behind a three-dimensional steep hill. *J. Wind Struct.* [In press].
6. Khankari, K. et al. (1997) Computational analysis of ceiling inlet ventilation systems for livestock buildings. *In* Proceedings of the fifth international symposium of livestock environment, Minnesota, 1, 32–39.
7. Korthals, R. et al. (1997) Swine feeding behavior and body temperature responses to an extended stepped temperature increase. *In* Proceedings of the fifth international symposium of livestock environment, Minnesota, 2, 781–788.
8. Launder, B. E. & Spalding, D. B. (1974) The numerical computation of turbulent flows. *Comput. Methods Appl. Mech. Engineer.*, **3**, 269–289.
9. Lee, I. B. et al. (2002) Study of livestock housing ventilation by aerodynamic approach. *In* Proceedings of annual meeting of the Korean society for livestock housing and environment, ed. Lee, I. B., Korean Society for Livestock Housing and Environment, Suwon, Korea, 51–58.
10. Reichrath, S. & Davies, T. (2002) Using CFD to model the internal climate of greenhouses: past, present, and future. *Agronomie*, **22**, 3–19.
11. Sun, H., Keener, H. & Michel, F. (2002) Comparison of predicted and measured ammonia distribution in a High-Rise Hog Building (HRHB) for summer conditions. ASAE Paper No. 024117. St. Joseph, Mich., USA.
12. Wathes, C. & Charles, D. (1994) Livestock housing. CAB International, Wallingford, UK, pp.428.
13. Wu, B. X. & Gebremedhin, K. G. (2002) Evaluation of turbulence models for predicting flow fields in a multi-occupant ventilated space. ASAE Paper No. 024102. St. Joseph, Mich., USA.