Development of an Air-Recirculated Ventilation System for a Piglet House, Part 1: Analysis of Representative Problems through Field Experiment and Aerodynamic Analysis Using CFD Simulation for Evaluating Applicability of System

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Abstract: As the pig industry develops rapidly, various problems are appearing both inside and outside the pig houses. In particular, in the case of pig houses, it is difficult to solve the main problems even if automation and mechanization are applied with ICT technology. The main current issues are: (1) preventing infectious diseases amongst livestock, (2) reducing the emission of harmful gas and odors, (3) improving the growth environment inside the pig house, (4) reducing energy costs, (5) improving the farm management and operating system, and 6) improving the livestock product quality. Air recirculation technology can be applied as a technology that can solve these typical problems in the pig industry. An air-recirculated ventilation system can minimize the inflow of air from outdoors and recycle the internal thermal energy of the pig house. The air-recirculated ventilation system consists of (1) an air scrubber module, (2) external air-mixing module, (3) UV cleaning module, (4) solar heat module, and (5) air-distribution module. First, in this study, the field data were collected to analyze the main problems of the target piglet house for the application of the air-recirculated ventilation system. In addition, a computational fluid dynamics (CFD) model was developed and validated for seasonal aerodynamic analysis. The applicability of the air-recirculated ventilation system was evaluated based on the CFD computed results for various environmental conditions. As a result of evaluating the internal environment according to the ventilation rates and external-air-mixing ratio of the air-recirculated ventilation system, the required ventilation rate and external air-mixing ratio to maintain the proper temperature and gas concentration were determined.

Keywords: air-recirculated ventilation system; computational fluid dynamics; field experiment; piglet house; validation

1. Introduction

1.1. Background of the Study

Due to the increase in economic development and innovation in the food distribution structure, the demand for meat and other livestock products has increased rapidly,
accounting for about 39.4% of the total agricultural production [1]. In particular, the pig industry occupies the highest proportion in the livestock industry, mainly due to intensive pig production, resulting in an increased number of animals produced per farm. However, the pig production increase caused a lot of contaminants to accumulate inside compared to other livestock facilities [2]. This also resulted in difficulties in maintaining the stability and uniformity of the growth environment in large-sized pig houses. The ventilation is generally operated to control the growth environment inside the pig houses. However, there are many difficulties in proper ventilation operation in pig houses. In many farms, the minimum ventilation rate is performed to minimize the inflow of cold air and maintain the optimum temperature in the winter season. Additionally, there is a reason for the reluctance to increase the ventilation rate. Epidemic diseases can be spread through the air, and environmental problems can occur near the pig farm when harmful gases and odors are dispersed from the pig farm. Accordingly, interest in technology that can improve the external environment as well as the growth environment inside the pig house is increasing.

Due to the presence of four distinct seasons in Korea, the problems of air temperature inside the pig house occur annually. The thermal environment inside the pig house consists of the sensible and latent heat generation of pigs and loss through ventilation and heat conduction from the wall. In particular, heat accumulation can occur inside the pig house even if the maximum ventilation is operated during summer. Exposure to a high-temperature environment for an extended period results in a 7 °C increase in a pig’s body temperature. In addition, the feed intake of pigs can be reduced by half when the temperature inside the pig house increases from 20 °C to 30 °C [3]. High stress in pigs was also found to increase the pig mortality from about 5000 heads in 2014 to 40,000 heads in 2018 [4]. Low temperatures also affect pig productivity. Pigs maintain their body temperature through metabolism. Therefore, the feed efficiency can be lowered because the metabolism can be increased when the air temperature near the pigs is lowered. Accordingly, it is not recommended to allow in a lot of cold air from outdoors in the winter season. In order to increase the pig productivity in summer and winter, it is essential to maintain the appropriate internal temperature. If additional air conditioners such as heaters and coolers are operated for temperature control, the energy input can be increased. Accordingly, although the minimum ventilation is operated in the winter season to maintain the temperature, other environmental conditions (e.g., humidity, dust, gas and odors) inside the pig house can be poor, leading to reduced pig immunity and the possibility of increased rates of respiratory diseases [5]. Therefore, it is essential to increase the ventilation rate while maintaining the appropriate temperature inside the pig house. In addition, there are various problems not only inside but also outside the pig house. One of the main functions of ventilation in the pig house is to keep the proper environment inside the pig house by exhausting the polluted air. However, harmful gases and odors emitted by ventilation fans can affect the external environment. There are reports that ammonia causes soil acidification and can be oxidized to sulfuric acid and nitrification in the air to generate secondary inorganic aerosols [6]. An increase in civil complaints about livestock odors and harmful gas emissions represents a big obstacle to the development of the pig industry. Therefore, there is a need for a technology capable of managing the environment inside and outside the pig house.

The air-recirculated ventilation system has been proposed as a method to improve the internal environment of pig houses, prevent livestock disease, and minimize the emission of harmful gases and odors. The main purpose of the air-recirculated ventilation system is to minimize the inflow of external air to prevent disease and increase the energy efficiency. It also minimizes complaints from residents by reducing odors and harmful gases emitted from the pig house. The ventilation rate can be increased without additional energy because the metabolic energy inside the pig house can be reused. Through this, there is the advantage that the internal growth environment can be improved.
The operation principle of the air-recirculated ventilation systems starts with sufficiently washing the internal air through the wet scrubber module wherein a certain amount of air is exhausted while a certain amount of air is mixed with fresh air and flows back into the system. These air recirculation technologies are mainly being studied in the industrial environment to save the cost of cooling and heating buildings [7–14]. In industrial processes, the standards for air recirculation have been developed, and standards for the allowable concentration of hazardous substances in the reused air are presented [15]. Accordingly, various studies have been conducted to apply the air recirculation technology to pig houses and devise a method of recirculated air to remove dust by using a fabric filter and an electrostatic dust collector [7,9,11,16–19]. Although the concentration of dust in pig houses can be reduced by up to 60%, it is difficult to satisfy the allowable concentration standards. Anthony, Altmaier, Jones, Gassman, Park and Peters [17] analyzed the concentration of dust and carbon dioxide inside the pig house when the air recirculation system was used and reported that the air recirculation system is an alternative to prevent the deterioration of workers’ health. Wenke et al. [20] analyzed that the dust concentration was the lowest and the pig’s lung health was excellent when filters were installed in the air recirculation system. Peters et al. [21] evaluated the performance by applying a shaker dust collector in the air recirculation system. Park et al. [22] simulated the effect of the concentration of the pollutant in the pig house using mass and energy balance equations. Meanwhile, Mostafa et al. [23] applied a wet scrubber to the air recirculation system and reported that the wet scrubbing technique can reduce both ammonia and dust concentration without a negative effect on pigs.

The previous studies analyzed the removal efficiency of dust and gas by applying an air-recirculated system; however, it is insufficient to simultaneously evaluate the growth environment of pigs, such as the air temperature, humidity, gas concentration, dust, and so on. In particular, it is important to maintain the air temperature while maintaining an appropriate humidity, gas, and dust environment in the winter season. Therefore, a complex analysis of various environmental factors is required. Additionally, the air-recirculated ventilation system should be designed as a system in which the ventilation rate and external-air-mixing ratio should be controlled in real time according to the various environmental conditions inside and outside the pig house.

1.2. Overall Aim of the Study

The air-recirculated ventilation system for pig houses used in this study was developed in the A3EL (Aero-Environmental & Energy Engineering Laboratory) of Seoul National University. The research has been conducted for a total of 5 years since 2018. The overall schematic diagram of the ventilation system of the existing pig farm and air-recirculated ventilation system is shown in Figure 1.

Most of the existing ventilation systems exhaust the internal air using ventilation fans. Under this type of ventilation system, both cold and hot air circulate inside the pig house where the heat, moisture, dust, and odor are directly exhausted outside the building. The air-recirculated ventilation system reuses the heat energy of the exhausted air and can minimize the dispersion of harmful gas and odor. The overall development of the system is carried out in four steps as follows (Figure 2). (1) The analysis of environmental problems and improvement were first conducted through seasonal field experiments and CFD (Computational fluid dynamics) modelling on the experimental pig farm (Ecofarm, Sunchon City, Korea) where the air-recirculated ventilation system will finally be installed. (2) Optimized design for each module of the air-recirculated ventilation system using a numerical model and overall integrated system design were conducted. The individual upscaling of modules such as the wet scrubber module, solar energy module, and air-mixing module were conducted at the AcSEC-A3EL of Seoul National University in South Korea. (3) Validation was conducted after the design of the upscaled modules was optimized and they were manufactured at the AcSEC-A3EL. Based on this, an algorithm for real-time monitoring and integrated control was designed. Then, the wet scrubber module was also
validated on a real piglet house. (4) The finally developed air-recirculated ventilation system was installed in Ecofarm (experimental pig house), and the final validation studies and modification were conducted by season. The operation manual was made after applying the algorithm for automatic control of the system.

Figure 1. Schematic diagram of the conventional ventilation system and the developed air-recirculated ventilation system.
were used as input data and validation data for the CFD simulation. The model for the target pig house was designed, and then environmental analysis was conducted with the computed CFD results. The environment data inside and outside the pig house were measured through seasonal field experiments, and they were also used as input data and validation data for the CFD simulation. In addition, the improvement and applicability of the air-recirculated ventilation system were evaluated compared with the existing system by adding the module of the air-recirculated ventilation system in the CFD simulation model.

2. Materials and Methods

In this paper, the internal environment of the target pig house was analyzed through field experiments and CFD simulations (Figure 3). The measured data in the target pig house include the air temperature, humidity, gas (ammonia, carbon dioxide), and ventilation rate. Additionally, the external weather was monitored by the meteorological station installed in the target experimental pig farm. Based on these data, the analysis of seasonal problems occurring inside the pig house was conducted. In addition, the measured data were used as input data and validation data for the CFD simulation. The model for the air-recirculated ventilation system was integrated into the developed CFD model where the ventilation rate and external-air-mixing ratio of the air-recirculated ventilation system were used to evaluate CFD calculation. The air-recirculated ventilation system was installed on the real experimental piglet house, and seasonal validation experiments were conducted. In this paper, applicability was evaluated through the CFD simulation for the air-recirculated ventilation system, and the validation results of the real farm will be analyzed in the next sections of the paper.
2.1. Target Facility

A mechanically ventilated pig house in Sunchoen EcoFarm (34°55′17″ N, 127°22′8″ E), Jeollanam-do, South Korea, was selected as the target pig house where the air-recirculated ventilation system would be installed. About 950 piglets aged between 3 and 11 weeks were raised in the experimental pig house (Figure 4) during the period of the study. The dimension of the facility is 10.55 m in width, 31.25 m in length, and 2.6 m in height. There was a ceiling space 1.2 m-high above the pig house, and a corridor with a width of 1.25 m outside the pig houses. The stocking density was found to be 0.35 m²·head⁻¹, which was higher than the Korean stocking density standard of 0.24 m²·head⁻¹. The outdoor air can enter through the corridor windows openings and through the 5 rows of 7 ceiling slots at the top of each pig zone. Identical types of side exhaust fans and chimney exhaust fans with 141.6 CMM each were installed in the experimental pig house (COCO-630A, Dongsung Cocofan. Ltd., Gyeonggi-do, Korea). The required ventilation rate according to the number of piglets was 509.6 CMM, and the recommended ventilation rate in winter and summer was 101.2 CMM and 762 CMM, respectively [24].

The air-recirculated ventilation system was installed in the experimental pig house in December 2021. In the existing ventilation system, external air flows into the ceiling space from the corridor and then flows into the pig house through the ceiling slots. The air inside the pig house was then exhausted from the outside through the chimney exhaust fan. Whereas the side exhaust fan is used only for maximum ventilation rate in summer, in general, only the chimney exhaust fan is used for operating ventilation. If the air-recirculated ventilation system is applied, only the side exhaust fans are used for ventilation. The air inside the pig house passes through the wet scrubber module to remove the ammonia gas, dust, and odors. The mixture of cleaned air and external air will then be recirculated again in the pig house. An experiment and simulation studies were also conducted on individual modules to determine the optimal design characteristics of the air-recirculated ventilation system by A3EL research team. The removal efficiency of the ammonia gas calculated through the module experiment was used as an input data in the CFD model of this study. Based on these results, the internal environment of the pig house...
was evaluated according to the ventilation rate and external-air-mixing ratio. Because the UV module is used for the sterilization effect of air, it does not affect the internal environment. Additionally, the solar module is operated only when temporary heating is needed in the winter. Therefore, both the UV module and solar module are not considered in the analysis of the internal environment.

**Figure 4.** The structure and ventilation system of the experimental pig house.

### 2.2. Field Experiment

The environmental data such as the heat, moisture, ammonia level, and ventilation rate were measured through field experiments from January 2019 to December 2021. Based on the measured data, the internal environmental analysis and validation of the CFD model were conducted. A total of 980 piglets which were about 7 weeks of age were raised inside the target experimental pig house. To measure the internal air temperature and relative humidity, temperature and humidity sensors (SH-VT260VS, Sohatech, Seoul, Korea) were installed at 9 points inside the pig house at a height of 1 m. The same temperature and humidity sensors were also installed in the corridor. A wireless temperature and humidity sensor (UX-100-03, Onset Computer Corporation, Bourne, MA, USA) were also installed at difficult-to-reach sampling areas such as the pig house entrance and ceiling where the installation of wired sensors is difficult. The installation location of each sensor is as follows (Figure 5). A weather station was installed outside the pig house to measure the outside temperature, humidity, and wind speed in real time. In order to measure the ammonia concentration, complex gas meters (MultiRAE IR, RAE System, California, USA) were installed at 6 sampling points. Calibrated readings from gas detector tubes (GV-110s,
GASTEC, Kanagawa, Japan) were used to measure the ammonia concentration inside the pit because it is impossible to measure the ammonia concentration using the complex gas meters inside the pit while pigs are being raised. In the case of a ventilation fan, the ventilation rate may be lower than the design fan performance depending on the age of the fan, the shape of the internal structure and the inlet type, and so on [25]. Therefore, the actual ventilation rate of the exhaust fan was quantified by measuring the difference between the inside and outside static pressure of the exhaust fan according to the operating condition and linking it with the actual electricity consumption. The relationship between the static pressure difference inside and outside the facility and the ventilation rate are shown in Equation (1) [26]. Using a differential pressure sensor (Manometer, TSI, Shoreview, MI, USA), the static pressure of the exhaust fan was measured. The measurement location was in front of the exhaust fan (inside the piglet house) and outside duct of exhaust fan.

$$\Delta P = \left( \frac{\rho}{\rho_d} \right) \left( a_0 w^2 + a_1 Q w + a_2 Q^2 \right)$$

where $\rho$ is the air density at the inlet (kg·m$^{-3}$), $\rho_d$ is the air density at the outlet (kg·m$^{-3}$), $Q$ is the ventilation rate (m$^3$·s$^{-1}$), and $w$ is the variable fan operation rate (dimensionless). The difference in static pressure inside and outside the exhaust fan was measured.

![Figure 5](image-url)  
**Figure 5.** Installation location for each sensor inside the experimental pig house.

The difference in static pressure inside and outside the exhaust fan was measured. The fan performance curves by the design fan curve and the actual measured airflow rate are shown in Figure 6. Considering this reduction in airflow rate of the fan, the boundary conditions of the CFD model were used from the relational expression shown in Table 1. In addition, the actual ventilation rate was measured in real time at the pig house based on the conversion result of the actual airflow rate according to the static pressure applied to the exhaust fan. As a result of the measurement, the airflow rate was decreased by about 19% compared to the design ventilation rate.
Figure 5. Installation location for each sensor inside the experimental pig house.

Table 1. Results from measuring the ventilation rate of exhaust fan in the experimental pig house.

| Static Pressure (Pa) | Flow Rate (CMH) | Reduction Rate (%) |
|----------------------|-----------------|--------------------|
| 0                    | 8497            | 6835               | 19.6               |
| 10                   | 8061            | 6499               | 19.4               |
| 20                   | 7488            | 6046               | 19.3               |
| 30                   | 6778            | 5478               | 19.2               |
| 40                   | 5931            | 4787               | 19.3               |

2.3. Computational Fluid Dynamics

CFD is a technology that obtains numerical solutions for physical quantities such as the pressure, force, and temperature or visualizes physical and chemical phenomena through computer simulation. The environmental conditions or theoretical equations can be easily applied to perform simulation through a CFD model, and only steady-state analysis and transient-state analysis can be computed. CFD simulation is widely used in fluid phenomena including heat transfer, mass transfer, and chemical reaction, mainly in mechanical, chemical engineering, manufacturing, and industrial fields. In addition, CFD simulation is being used in various buildings such as greenhouses and livestock houses to estimate the heating and cooling, ventilation, wind load, odor dispersion, and so on. The equation required to analyze fluid and energy flows from CFD are nonlinear simultaneous partial differential equations obtained by applying the law of conservation of mass, momentum, and energy. The mass conservation equation can be applied regardless of whether the flow is steady, viscous, or compressible, and can be expressed as Equation (2). The momentum conservation equation is known as the Navier–Stokes equation, and it is expressed as Equation (3). The energy conservation equation can be defined as Equation (4) as an equation that stipulates the relationship of energy converted between physical systems.

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0
\]

\[
\frac{\partial}{\partial t}(\rho u_j) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial}{\partial x_j}(\rho \delta_{ij}) + \frac{\partial}{\partial x_j}(\tau_{ij})
\]

\[
\frac{\partial}{\partial t}(\rho e_0) + \frac{\partial}{\partial x_j}(\rho u_i e_0) = -\frac{\partial}{\partial x_j}(u_i p + q_j) + \frac{\partial}{\partial x_j}(u_i \tau_{ij})
\]
where \( u_j, u_i \) are the velocity in the direction \( i, j \) \((\text{m} \cdot \text{s}^{-1})\); \( p \) is the static pressure \((\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2})\); \( e_0 \) is the total energy \((\text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2} \cdot \text{kg}^{-1})\); \( \eta_j \) is the heat flux \((\text{W} \cdot \text{m}^{-2})\); \( \rho \) is the density \((\text{kg} \cdot \text{m}^{-3})\); \( \tau_{ij} \) is the stress tensor \((\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-2})\); and \( \delta_{ij} \) is the Kronecker delta function \((1 \text{ if } i = j, 0 \text{ if } i \neq j)\).

2.4. Experimental Procedure

In this study, the internal environmental factors were measured in the experimental pig house, and the result of the analysis was later applied for the development of the air-recirculated ventilation system. In addition, since it was difficult to analyze the aerodynamics and various conditions inside the pig house with live pigs, the CFD simulation modelling technique was additionally used to analyze the internal environment according to the ventilation rate and ventilation types. The CFD model was validated based on the measured data to evaluate the accuracy and reliability of the CFD model. In addition, it was attempted to evaluate the applicability of the air-recirculated ventilation system and to predict the environmental distribution.

2.4.1. Data Construction for Analysis of the Internal Environment of the Piglet House

The air quality (temperature, humidity, gas, and so on) inside and outside the pig house was measured every 5 s and stored at average of 5 min interval measurements in the database. The database also stored the power consumption of the exhaust fan, which was measured and converted into an equivalent ventilation rate. According to the ventilation conditions, the collected data were evaluated for whether ventilation was properly operated seasonally. The real-time measurements obtained by the installed sensors were also stored in the database. Each datum was monitored through a program built on the website. The data collection for big data construction was conducted using an open-source client program (HeidiSQL). HeidiSQL is a piece of DBMS (database management system) software that enables efficient data storage and management for communication between users and databases and supports search and data operation. The ID and sensor values defined in each sensor were matched to build real-time and continuous data. Since it was difficult to analyze and visualize the collected raw data in the direction of users, a program that can automatically collect and systematically visualize the data was coded and used in this study.

2.4.2. Data Processing Method of Measured Data

A time synchronization was conducted because the time of the collected data may be different depending on the time setting of each sensor. In addition, data filtering was needed since unnecessary redundant data can be collected in the data-collection process. Using the C language string function, duplicate data removal and time synchronization programs were designed and installed. In the data-collection field, the sensor ID can be defined by the developer. However, in the data-collection process, it is necessary to process the data defined in a row to fit each field row in order to improve the data-collection efficiency. Therefore, the first data-processing operation was conducted using the R program. After the first processing, the data were classified into fields according to the location and type of each sensor, and data visualization was conducted to analyze data easily. For data visualization, Excel and VBA (Visual Basic for Applications) program codes were used, and since the data collection period was long, visualization was made possible by dividing it into seasons, factors, and days. In this study, the time points corresponding to seasonal internal environmental problems and the cause analysis were found among the environmental monitoring results of the pig house. The data were divided into time series, and the internal environmental factors and ventilation rate were comparatively analyzed.

2.4.3. Design and Validation of CFD Simulation Model

The process of developing the CFD model was performed as follows: (1) design of the geometry, (2) meshing, (3) input of boundary conditions, and (4) calculation of the
CFD model. However, the development CFD simulation model has various uncertainties. First, uncertainty in the design of geometry may occur when the shape of the actual pig house is simplified for simulation or some shapes are excluded. In this study, all internal structures of the pig house were designed similarly except for thin pipes and wires that did not significantly affect the airflow, and the actual shape of the pigs were designed to be the size of a 7-week-old piglet. In addition, the ventilation structure was designed to have the same shape as the real pig house to reduce uncertainty as much as possible. Second, in the mesh design stage, it is important to design the grid distance as efficiently as possible. The larger the grid interval, the faster the simulation computation, but the resolution of the calculation results may be lowered and the accuracy may be lowered. In this study, the optimal number of grids was determined by the grid independence test comparing the calculation speed according to the shape and number of grids. The grid was designed by maintaining the skewness value, which is an indicator of grid quality. Third, the uncertainty may occur depending on the value input as the boundary conditions. The environmental variables to be analyzed in this study were heat, moisture, gas, and airflow. The input values of boundary conditions for each environmental variable were values measured in the field and values obtained by theoretical equations. Therefore, the similarity between the values measured in the field and the simulation results calculated based on the values obtained from the theoretical equations was confirmed. Additionally, different calculation equations are applied depending on the turbulence model to simulate the airflow. In the turbulence model, the types and methods of solving the equations are different depending on the CFD model. Therefore, by performing calculations according to various turbulence models, the turbulence model simulated most similar to the data measured in the field was selected as the final model. Finally, in the calculation stage, it can be divided into a steady-state and a transient state depending on the timing of the simulation. Since heat and gas generation per hour are applied, the transient state was simulated to consider the time interval.

To reduce the uncertainty of the CFD model simulation and improve the accuracy, verification of whether field-measured data was suitable for boundary conditions, and comparison with theoretical equations was conducted. Additionally, validation to improve the accuracy of simulation results was conducted through comparison of CFD computed results and field measured data. The theoretical verification was conducted with the thermal environment and the gas environment, which were the most important factors in the internal boundary condition.

When verifying the thermal environment, the boundary condition of the CFD model was applied based on the temperature data measured in the field, and the heat generation was compared with the simulation result and the heat generation rate of piglets provided by [27]. To simulate the heat generation rate of piglets in the CFD model, the surface condition of a piglet was divided into the surface of skin for body heat and the surface of the mouth for respiration. Both the heat transfer in the air and conduction to the floor inside the pig house were ignored, and only heat generated by latent heat and sensible heat was considered. In the case of a gas environment, the generation rate per unit time in the pit space of the CFD model was simulated based on ammonia data measured inside the pig house, and verification of the boundary condition was conducted compared with the amount of ammonia generated according to the domestic emission factor.

In order to improve the accuracy of CFD simulation, the grid independence test and turbulence model test were conducted to increase the computational efficiency of the model. For the grid independence test, a grid size with sufficient quality was selected by comparing the calculation time according to the number of grids of the model and the skewness of the grid. Additionally, based on the temperature data measured in the piglet house, the turbulence model was selected by conducting comparative validation according to the turbulence models. Finally, CFD models were computed based on the models which were conducted for verification of boundary conditions and validation of grid independence test and turbulence models.
2.4.4. Boundary Conditions of CFD Simulation Model

The boundary conditions finally used for the calculation of the CFD simulation model designed in this study is shown in the Table 2. The heat, moisture, and gas generation were applied as values determined through verification, and ventilation rates were applied in consideration of the fan load. The heat source inside the piglet house was simulated by the pig’s body surface and breathing. For the surface temperature of the pig, the actual measured value of the surface temperature of the pig was applied. Since the temperature of the pig’s breathing air is equal to the body temperature, the sensible heat caused by respiration was applied as the body temperature of the piglets in the boundary condition. Additionally, the moisture generation rate was included in the respiration of piglets (Figure 7).

Table 2. Boundary conditions of CFD simulation.

| Types                        | Values   | Units |
|------------------------------|----------|-------|
| Outdoor temperature          | Winter   | −8    | °C    |
| (TAC: 5%)                    | Summer   | 33    |       |
| Air temperature inside the corridor | Winter | 10    | °C    |
|                             | Summer   | 31    |       |
| Heat production              | Surface temperature of piglet | 39.7  | °C    |
| Breathing capacity           | 0.28     | m³·h⁻¹·s⁻¹ |
| Moisture production of piglets | 1.7      | g·h⁻¹·kg⁻¹ |
| Moisture generation rate of manure | 2.8      | g·h⁻¹·kg⁻¹ |
| Ammonia generation rate of manure | 211.4   | g·h⁻¹  |
| Validation                   | 0.6      |       |
| Ventilation rate             | Winter   | 0.12  | min⁻¹ |
|                             | Summer   | 0.92  |       |

Solver Pressure-based solver -
Numerical algorithm SIMPLE algorithm -
Time condition Steady state -
Operating pressure 1.1325 Pa
Gravitational acceleration 9.81 m·s⁻²
Air density 1.225 kg·m⁻³
Air viscosity 1.7894 × 10⁻⁵ kg·m⁻³·s⁻¹
Ammonia density 0.6894 kg·m⁻³
Ammonia viscosity 1.015 × 10⁻⁵ kg·m⁻³·s⁻¹
H₂O density 0.5542 kg·m⁻³
H₂O viscosity 1.34 × 10⁻⁵ kg·m⁻³·s⁻¹

Figure 7. Heat generation rate of body surface of pig and breathing.

Moisture and ammonia generation rates from the manure were simulated to generate and diffuse from the pit space located at the bottom of the piglet house. The moisture generation rate was applied in consideration of the ratio between the size of the pig
house used in the previous study and the size of the pig house applied in this study [28].
In addition, the ammonia generation rate was converted to the ammonia concentration measured in the experimental piglet house and applied in the CFD model. The moisture and ammonia gas should pass through the pit slot on the bottom to diffuse from the pit space. The airflow can be resisted by the structure of the pit slot. Therefore, the floor of the pig house was designed as a porous medium for the efficiency of the calculation considering the effect of diffusion of moisture and ammonia gas inside the pit. When passing through the area of the porous medium, the element resisting the flow in the \( x \), \( y \), and \( z \)-axis directions can be calculated and expressed through Equation (5) [29]. Considering the shape of the pit, the airflow in the vertical direction exists and the air flow in the horizontal direction is limited.

\[
\Delta p = 0.5 \times R_1 \times \rho \times \sigma^2 + \mu \times R_2 v
\]

where \( \Delta p \) is the pressure change in the porous medium (Pa), \( R_1 \) is the internal resistance factor, \( R_2 \) is the viscous resistance coefficient, \( \rho \) is the density of air (kg·m\(^{-3}\)), \( \sigma \) is the velocity flowing in the porous medium (m·s\(^{-1}\)), and \( \mu \) is the viscosity coefficient of the air (kg·m\(^2\)·s\(^{-1}\)).

When the air-recirculated ventilation system is applied to the validated CFD model, the inlet and outlet of the pig house can have the outlet and inlet wet scrubber module applied, respectively. Therefore, the environmental values of the air exhausted from the pig house are converted by the characteristics of the wet scrubber module, and the air is mixed with the external air. When analyzing the air-recirculated ventilation system, the heat, moisture, and gas generation rate of the validated CFD model were equally applied. If an air-recirculated ventilation system is installed, the performance of the equipment can be assumed to be its own capacity, and it can be operated by controlling the ventilation rate and the external-air-mixing ratio. Additionally, the removal efficiency of the wet scrubber module depends on the ventilation rate, type of fills, type of recirculation water, and so on. Therefore, for CFD simulation, the characteristics of the wet scrubber module should be numerically applied. In this study, the results of previous research on each module of the A3EL research team were used. After determining the characteristics of the wet scrubber module based on the experimental results for various variables (type of nozzles, fills, recirculation water, and so on), in the CFD simulation, the removal efficiency of 77, 64, 54, and 49% were assumed depending on the ventilation rate of 25, 50, 75, and 100%. The condition of the air passing through the wet scrubber can converge to the temperature of the recirculation water with a relative humidity at 100%. The recirculation water is initially the same as the temperature of the groundwater, but it can converge to a certain temperature in contact with the air inside the pig house. When the initial temperature inside the pig house was assumed to be 30 °C and with a relative humidity of 60%, it converges to about 24 °C based on repeatedly calculating the heat exchange. Therefore, the recirculation water temperature was set to 24 °C in the CFD simulation model. The boundary conditions applied to the CFD model are shown in Table 2.

2.4.5. Case Studies of CFD Simulation

In this study, an analysis of the internal environment and seasonal problems of the target pig house was conducted based on the data measured in the field experiment. CFD simulation was used to aerodynamically analyze the causes of these problems. First, the main environmental problems such as internal temperature, humidity, and gas were analyzed based on the computed results of the CFD simulation (Table 3). It is necessary to compare the difference according to the operating conditions of the ventilation (ventilation rate, inlet type, and so on) to suggest the improvement method for these problems. Therefore, the CFD model that was previously analyzed in the winter season was used to analyze the operating condition when the ventilation rate was increased and the radiator was added. In addition, the evaluation according to the ceiling slot condition was conducted to analyze the internal uniformity as shown in Table 3. Finally, at the same ventilation rate, the internal environment of the pig house was comparatively analyzed based on the
computed results when the air-recirculated ventilation system was applied. To evaluate the applicability of the air-recirculated ventilation system, the internal growth environment was analyzed according to the ventilation rate and external-air-mixing ratio. The total number of case studies for the CFD simulation was 37.

Table 3. Case studies of the CFD simulation in this study.

| Purpose                                                                 | Experimental Variables                                                                 | Cases |
|------------------------------------------------------------------------|----------------------------------------------------------------------------------------|-------|
| Analysis of the internal environment by season                         | Outdoor weather condition: winter & summer                                               | 2     |
| Analysis of internal environment according to the increase             | Ventilation rate: 0.06, 0.12, 0.18, 0.24, 0.3 min\(^{-1}\)                            | 20    |
| of ventilation rate using radiator in winter season                     | Radiant values of radiator: 0, 500, 600, 650 W                                         |       |
| Analysis of internal environment according to the ceiling slot conditions| Open conditions of ceiling slots: 3 types Ventilation rate: 0.12, 0.24 min\(^{-1}\)     | 6     |
| Analysis of the internal environment according to the operating conditions of the air recirculation system | Ventilation rate: 0.2, 0.6, 0.9 min\(^{-1}\) Mixing ratio of outdoor air: 25, 50, 75% | 9     |

3. Results and Discussion
3.1. Analysis of Internal Measurement Data of Piglet House in Summer and Winter
3.1.1. Results of Summer Season

Figure 8 shows the air temperature, ventilation rate, and gas measurement results inside the pig house in summer. The aim for temperature of the experimental piglet house was about 28 °C. The chimney exhaust fan was operated according to the internal temperature. When the weather was hot, additional ventilation was operated using the side exhaust fans to increase the ventilation rate. The highest temperature outdoors on 6th and 7th August was kept high at about 34 °C, and the lowest temperature at nighttime showed a temperature distribution of 24 °C. Due to the hot weather outside, as shown in Figure 8b, the ventilation rate was temporarily high. As the ventilation rate increased, the air exchange rate was high, so the temperature inside the pig house was greatly affected by the external air. As a result, a ventilation rate of 1.4 min\(^{-1}\) during the daytime was operated, and the air temperature inside the ceiling and the pig house reached about 33 °C. If the target temperature rises by 5 °C compared to the target temperature of 28 °C, there may be a problem that the daily weight gain of piglets decreases by about 16.8% from 467.6 g day\(^{-1}\) to 388.6 g day\(^{-1}\) [30]. Because the experimental pig house did not use the additional cooling system, the method to lower the temperature inside the pig house was limited in the current operation method. At nighttime, the target temperature was kept close to 28 °C with a low ventilation operation of 0.2 min\(^{-1}\) despite an external temperature of 25 °C due to the heat production of the piglets. During the daytime on 8 and 9 August, the external temperature was 27 °C and 32 °C, respectively, but the low ventilation rate led to less air exchange inside the pig house and the target temperature could be maintained. In the case of the ceiling space, which is an inflow path of external air, an average of 26 °C was maintained, lower than the temperature inside and outside the pig house. The roof of the experimental pig house was made of 175 mm hard urethane panels, which is more than double the recommended thickness of 75 mm in the southern region of Korea [1]. Accordingly, due to the high thermal insulation effect, the heat accumulation inside the ceiling space did not occur significantly, and the temperature was maintained lower than the outside and inside of the pig house. Figure 8c shows the measured data of the ammonia concentration inside the piglet house. During the daytime on 7 August, when the ventilation rate was temporarily increased, the concentration of ammonia gas was as low as about 6 ppm, but it was maintained at around 20 ppm during the summer season due to the overall low ventilation operation. When the external temperature rose greatly, the farmer tried to prevent the internal high temperature stress by artificially increasing the ventilation rate. However, there was a problem that the air temperature rose because there was no cooling system. In order to resolve these problems, ventilation with a cooling system controlled according to the temperature distribution inside and outside is required. It is expected that high temperature stress can be prevented by operating the air-recirculated ventilation...
A system equipped with a wet scrubber method that has a cooling effect in this experimental pig house. In addition, the internal ammonia gas could not be removed because of the low ventilation rate. Therefore, it is possible to improve the gas environment by increasing the ventilation rate through the air-recirculated ventilation system.

Figure 8. The air temperature, ventilation rate, and ammonia gas results measured in experimental piglet house in summer season. Data analysis period of 6 August (5 weeks piglet) when heat stress was occurred.

3.1.2. Results of Winter Season

Figure 9 shows the temperature, ventilation rate, and gas measurement results inside the pig house in winter. The pig breeding period was from 12 November to 28 December.
3.1.2. Results of Winter Season

Figure 9 shows the temperature, ventilation rate, and gas measurement results inside the pig house in winter. The pig breeding period was from 12 November to 28 December 2021. The standard operating temperature was maintained at 30 °C initially and lowered by 1 °C every week to 25 °C at the end of rearing period. To maintain the internal temperature in the piglet house, the radiator was operated in stages according to the age of the week, and the operating temperature of the radiator is shown in Figure 9a. The set temperature of the radiator was lowered every week, but as the weight and heat production of internal pigs rose, the temperature inside the pig house was maintained within a deviation of 2 °C. It is considered that the internal air temperature was well operated by maintaining the internal temperature of the pigs from about 30 °C to about 26 °C. During the rearing period, the external temperature was formed at about 20 °C during the daytime, and the difference in air temperature between the outdoor and inside of the ceiling was maintained at about 1 °C. Meanwhile, during the nighttime, the temperature dropped sharply, and the external temperature dropped to a minimum of −10 °C. However, the ceiling space was able to maintain a temperature higher than 0 °C due to the excellent insulation of the roof. During the winter season, the minimum ventilation rate was maintained at around 0.07 min⁻¹, which was lower than the minimum ventilation rate of 0.12 min⁻¹ based on the MWPS standards. Therefore, the proper temperature inside the piglet house was maintained through the body heat produced by the piglets, the operation of the radiator, and the operation of the minimum ventilation rate. At the beginning of rearing, the concentration of carbon dioxide gas and ammonia gas inside the pig house were 1200 ppm and 38 ppm, respectively. In this experimental piglet house, manure was not cleaned before raising piglets and ventilation was not performed. Therefore, the gas state inside the piglet house was higher than the allowable atmospheric carbon dioxide concentration of about 300 ppm, and the ammonia gas concentration was as high as about 38 ppm. In the first week, the exhaust fan was operated at the ventilation rate of 0.2 min⁻¹, and the internal ammonia concentration was lowered to about 10 ppm because the amount of gas discharged was larger than the generation rate. This showed a similar trend to the ammonia concentration in the summer operating with a ventilation rate of 0.2 min⁻¹. However, since 20 November, the ventilation rate was operated at 0.07 min⁻¹, and the concentration of internal carbon dioxide and ammonia gas showed a continuous increase. The amount of carbon dioxide generated is closely related to the respiration of pigs, and the amount of respiration of pigs is positively correlated with internal air temperature and raising period [31]. Theoretically, sufficient ventilation should be performed to lower the gas concentration as the age of the piglets increases. However, in this experimental piglet house, the internal gas environment was maintained very poorly because less ventilation was performed for maintaining the air temperature. Accordingly, since the ventilation rate was low, the ammonia gas concentration was measured to be above the allowable gas concentration of 20 ppm. As the age of the piglets increased, the gas generation rate in the manure increased, so the internal ammonia concentration eventually increased by more than 50 ppm. It is necessary to lower the ammonia concentration through sufficient ventilation because this can greatly reduce the feed efficiency and immunity of piglets.

In this experimental piglet house, ventilation was hardly operated to maintain the internal air temperature in winter. Therefore, it was concluded that the application of the air-recirculated ventilation system is necessary to improve the gas environment by increasing the ventilation rate. In addition, the air discharged through the air-recirculated ventilation system is advantageous in resolving complaints because the odors and harmful gases can be reduced. It also has an advantage in preventing the inflow and outflow of infectious livestock diseases in the winter.
Figure 9. The air temperature, ventilation rate, and ammonia gas results measured in experimental piglet house in winter season.

(a) Air temperature (piglet room, ceiling and outdoor)

(b) Ventilation rate of piglet room

(c) Concentration of NH₃ in piglet room
3.2. Verification and Validation of CFD Simulation Model

3.2.1. Verification of Boundary Conditions

To verify the boundary condition input value of the CFD simulation, the calculated value based on the theoretical equations and the calculated value using the CFD simulation model were compared and analyzed. First, in order to verify the boundary condition for the thermal environment, the heat production of the simulation model was calculated (Table 4).

In general, the flow of internal thermal energy in a piglet house is heat generated by animals, the conduction of external solar energy by walls, and heat transfer to the ground. The roof and walls of the experimental pig house were not exposed to the outside and are adjacent to the corridor, the ceiling space, and other pig houses. Additionally, the thickness of the wall was more than twice that of the standard pig house. Therefore, in this study, the heat transfer from walls and floors and heat transfer by external solar radiation were not considered. In a previous study, the heat production of pigs was considered as body heat on the pig’s surface to simulate sensible heat production [32]. Since the short-term behavior of air, heat, and gas in a transient state was analyzed to simulate the heat generated over time, in this CFD model, not only the body heat of the piglet but also the heat production per hour through the respiration of the piglet was considered. In the CFD model applying the temperature data measured in the field, the total energy by respiration was calculated to be 26,567 W, and the heat flux generated from the pig’s surface was multiplied by the surface area to calculate the heat production of 9235 W. Therefore, the total heat production of 35,803 W, which is the sum of the two calculated results, was derived (Table 4). Next, to verify the heat production based on the theoretical equation, 35,476 W was derived by multiplying the total heat production value, the sum of latent heat and sensible heat, by the actual number of piglets based on the heat production of piglets provided by International Commission of Agricultural and Biosystems Engineering [27]. Therefore, since the error between the two calculated values was within 0.9%, it is considered that the internal thermal environment was appropriately simulated in the CFD model to which respiration and surface heat were applied based on the data measured in the field.

Table 4. CFD computed results of respiration and body heat production of piglets and calculated results of theoretical heat production.

| Conditions          | Parameter                  | Heat Generation Rate | Unit        |
|---------------------|----------------------------|----------------------|-------------|
| CFD computed data   | (a) Breath of piglets      | 26,567.6             | W           |
|                     | (b) Body heat of piglets   | 9235.5               | W           |
|                     | (a) + (b) Total            | 35,803               | W           |
| Theoretical calculation | Total heat production    | 94.8                 | W kg⁻¹ yr⁻¹ |
|                     | Latent heat production     | 58.6                 | W kg⁻¹      |
|                     | Sensible heat production   | 36.2                 | W kg⁻¹      |
|                     | 980 head × 20 kg × SHP     | 35,476               | W           |

The ammonia generation rate in pig houses differs depending on the air temperature inside the pig house and the surface flow rate of manure [33]. The method of constantly generating the ammonia gas on the surface of the manure in the CFD simulation model is inappropriate for simulating the diffusion of ammonia by the air flow because the constant flow rate is fixed. Therefore, in this study, boundary conditions were set so that ammonia values were diffused in the pit space according to the surrounding concentration and flow rate. In addition, the ammonia concentration value calculated in the CFD model was analyzed and compared with the domestic ammonia emission factor. The domestic emission factor is 1.89 kg animal⁻¹ yr⁻¹ based on piglets. As shown in Table 5, the amount of ammonia generation rate inside the experimental piglet house was calculated. The ammonia concentration (ppm) measured in the experimental piglet house was listed according to time, and the hourly generation rate was calculated using the volume and ammonia density in the pit space. In this case, the ammonia generation rate was $2.82 \times 10^{-7}$ kg m⁻³ s⁻¹.
and the emission factor standard was $2.98 \times 10^{-7}$ kg·m$^{-3}$·s$^{-1}$. The error between the two values was calculated to be within 5%. Therefore, it is considered sufficient to be applied as a CFD boundary condition.

Table 5. Ammonia generation rate of CFD computed results and emission factor of domestic standard.

| Conditions          | Parameter                          | Gas Generation Rate | Unit   |
|---------------------|------------------------------------|---------------------|--------|
| CFD computed data   | Concentration of NH$_3$ in pit slurry | $2.82 \times 10^{-7}$ | kg·m$^{-3}$·s$^{-1}$ |
| Theoretical calculation | Emission factor of piglet             | $2.98 \times 10^{-7}$ | kg·m$^{-3}$·s$^{-1}$ |

3.2.2. Validation of CFD Simulation Model for Computational Efficiency

The geometry of the experimental piglet house was sufficiently designed since the locations of all inlet and outlet ports except for the pit shape were patterned based on the actual design of the piglet house. In order to design the mesh of the CFD model, a grid independence test was conducted by comparing the calculation speed of the basic model according to the size and number of grids. First, the optimal grid size was selected by comparing the basic model calculation time according to the number of grids with skewness, a statistical index indicating grid quality. In general, as the number of grids in the model increases, the accuracy of the calculation results improves. Errors were found when larger grids were used. However, as the number of grids increases, the computation load increases rapidly, and the accuracy does not significantly improve beyond a certain number of grids and skewness quality. Skewness according to the number of grids is shown in Figure 10, and the grid size was corrected for optimal operation of the model. The results according to the number of grids and the calculation speed according to the grid size are shown in Figure 11. In this study, when the number of grids was about 6.9 million, the skewness value was designed as 0.92 and the minimum value of orthogonal quality was 0.213, and these grid conditions were used for calculating the CFD model.

Figure 10. Results of the meshing of CFD model according to the size and number of grids.
3.2.3. Validation of CFD Simulation Model for Improvement of Uncertainty Variables

Using the model in which the boundary condition verification for the experimental piglet house has been completed, the validation was conducted based on the measured data in the experimental piglet house. The accuracy of the model was improved by conducting comparative validation according to the turbulence model based on the May 2020 field measurement data. At the time of the field experiment, the external air temperature was 27.3 °C, the humidity was about 60%, and the ventilation was operated at 0.6 min⁻¹. Internal air temperature data of the piglet house were used for the validation data, and the Realizable k-ε, Standard k-ε, RNG k-ε, and Standard k-ω were used as validation variables for the turbulence models. The difference between the computed data and the measured data according to the turbulence model is shown in Table 6. The external air entering the corridor of pig house was at a temperature of 27.3 °C. As the heat was lost through the floor and walls inside the corridor, the temperature was lowered to about 25 °C, and the air flowed into the piglet house through the ceiling space of the piglet house. The heat of the piglet house was transferred to the ceiling, and the air temperature rose again and recovered to an average of 27 °C in the ceiling space. This showed a tendency to recover heat while moving from the corridor to the opposite of the corridor. Accordingly, the temperature distribution of T-1, T-4, and T-7 was lower than that of the opposite sides (T-3, T-6, and T-9) due to the inflow of fresh air, which is the closest to the corridor. In addition, the lowest temperature distribution was shown in T-2, T-5, and T-8, where the airflow was formed by the exhaust fan because the heat inside the piglet house was discharged well. Among the turbulence models, the RNG k-ε model, which had the smallest error with field measurement data, showed results within 2% of error. Therefore, in this study, the RNG k-ε model was selected as the turbulence model.
Table 6. Measured and CFD computed air temperature and error according to the turbulence models.

|                   | T-1  | T-2  | T-3  | T-4  | T-5  | T-6  | T-7  | T-8  | T-9  |
|-------------------|------|------|------|------|------|------|------|------|------|
| Measured data     |      |      |      |      |      |      |      |      |      |
| Temp (°C)         | 30.6 | 30.7 | 31.1 | 30.7 | 30.5 | 30.9 | 30.5 | 30.3 | 30.8 |
| Error (%)         | 2.9  | 2.7  | 1.4  | 2.8  | 3.2  | 1.9  | 3.7  | 3.7  | 2.0  |
| Realizable k-e    |      |      |      |      |      |      |      |      |      |
| Temp (°C)         | 31.5 | 31.5 | 31.5 | 31.6 | 31.5 | 31.5 | 31.6 | 31.4 | 31.4 |
| Error (%)         | 2.8  | 2.1  | 1.4  | 1.9  | 2.2  | 1.9  | 3.1  | 4.2  | 2.0  |
| Standard k-e      |      |      |      |      |      |      |      |      |      |
| Temp (°C)         | 31.5 | 31.3 | 31.5 | 31.3 | 31.2 | 31.5 | 31.4 | 31.6 | 31.4 |
| Error (%)         | 2.8  | 2.1  | 1.4  | 1.9  | 2.2  | 1.9  | 3.1  | 4.2  | 2.0  |
| RNG k-e           |      |      |      |      |      |      |      |      |      |
| Temp (°C)         | 31.1 | 31.2 | 31.4 | 31.1 | 31.0 | 31.4 | 31.0 | 30.9 | 31.2 |
| Error (%)         | 1.5  | 1.5  | 1.0  | 1.4  | 1.7  | 1.7  | 1.9  | 1.9  | 1.5  |
| Standard k-w      |      |      |      |      |      |      |      |      |      |
| Temp (°C)         | 31.6 | 31.1 | 31.0 | 31.5 | 31.5 | 31.4 | 31.5 | 31.3 | 31.5 |
| Error (%)         | 3.1  | 1.3  | 0.2  | 2.5  | 3.3  | 1.6  | 3.5  | 3.2  | 2.4  |

The location of measurement and measured data of ammonia concentration are shown in Figures 12 and 13. The measured ammonia concentration was lower near the entrance than near the exhaust fan. It is considered that the concentration difference occurred because the fresh air in the corridor first entered from the location close to the corridor among the ceiling slots. The concentration of the side parts (L1, L2, R1, R2) was measured to be 7 ppm higher than the central part of the piglet house, and a concentration of 20 ppm or more occurred on the left side (L1, L2). The CFD simulation results showed that the left and right concentrations were symmetric, but in the field measurement data, the R1 and R2 points were lower than the L1 and L2 points. This difference occurred because of the difference in the manure condition inside the pit. Since the experimental piglet house was operated as an all-in–all-out system, the manure condition on both sides of the pit was also different. Accordingly, the difference in ammonia concentration occurred, and it was not realistic to consider this situation in CFD. In addition, as the piglets age, the condition of the manure becomes almost the same. Therefore, the CFD simulation was conducted assuming that all the manure conditions were similar.

Figure 12. Computed results of ammonia concentration inside the experimental piglet house.
The results of the CFD simulation for the winter season in Korea are shown in Figure 14a. In the case of the external temperature of 10 °C, the simulation was computed under the conditions of the minimum ventilation rate (0.07 min⁻¹), and the temperature and ammonia contours at the height of the piglet zone are shown in Figure 14. In this case, the average air temperature inside the piglet house was maintained at an appropriate level (about 29 °C). This showed similar results to the previous field measured results in the winter season. An approximately 22 °C air temperature was computed when the air flowed in from the corridor passed through the ceiling space. A temperature distribution of about 25 °C was shown at the lower part of the ceiling slot close to the corridor. Since this cannot be measured using the temperature sensor in the field, the aerodynamic analysis of the internal environment distribution was conducted through CFD simulation. The air was heated while moving to the exhaust fan, so it was possible to prevent low temperature stress inside the piglet house. The heat source inside the piglet house was the piglet’s heat production and radiator heating. Because this simulation was the result of computing the thermal environment of 5-week-old piglets without operating the radiator, operating the minimum ventilation rate was a suitable condition for the piglets. However, if the piglets have high heat production, the amount of weight gain due to feed intake may decrease due to the increase in the metabolic rate. Accordingly, the farmers try to reduce the heat production of the piglets by operating the radiator.

In the case of the ammonia concentration, it was confirmed that the ammonia concentration accumulated as the distance from the corridor was increased, and the concentration was high on both sides of the piglet house. Unlike the ammonia concentration measured in the field, the distribution of ammonia concentration around the piglet zone showed a maximum of 40 ppm of the internal deviation, and the area where the ammonia concentration was improperly distributed was more than 65% of the entire piglet house. Since the air temperature of the inlet is important for controlling the thermal environment, the location and distribution of the inlet are important. However, in the case of ammonia gas, the location where inlet is and the ventilation rate of the fan should be considered. The chimney exhaust fan and the ceiling slots installed in the center of the experimental piglet house were located at sufficient intervals, but the ceiling slots installed close to both walls were located adjacent to the chimney exhaust fan. This may cause a problem that the fresh air flowing into the side of the piglet house is not sufficiently supplied to the piglet.
zone and discharged through the exhaust fan. The average ammonia concentration inside the piglet house was 40.1 ppm, which was a very dangerous level, and it was predicted that the productivity decrease due to the high concentration of gas could occur when the minimum ventilation is operated in the winter season. Therefore, it is judged that the operation of the minimum ventilation rate in winter did not sufficiently remove the internal ammonia gas, and it is necessary to increase the ventilation rate using the air-recirculated ventilation system.

The results of CFD simulation for the summer season (outdoor temperature of 34 °C) in Korea are shown in Figure 14b. In the experimental piglet house, the maximum ventilation of 1.4 min⁻¹ was operated even in summer when it was extremely hot, and 0.2 min⁻¹ was usually used. In this study, the CFD models were computed under the condition of the maximum ventilation rate, and the air temperature near the piglet zone was maintained at an average of 32.05 °C. In general, in summer, a high ventilation rate is maintained to remove the heat inside piglet house. However, when the outdoor weather conditions are very hot, the inflow air should be cooled. In the experimental piglet house, the external air was flowed in and the air temperature was lowered by 2 °C in the corridor. Due to the high ventilation rate, the air inside the piglet house was replaced quickly, and the internal air temperature converged to about 32 °C. If the average temperature inside the piglet house is

![Figure 14. CFD computed results of visualization of the internal air temperature and ammonia concentration contour of the experimental piglet house in winter and summer.](image-url)
maintained above 32 °C, productivity may be lowered due to the high temperature stress, so it is considered that a cooling device is necessary. Since the wet scrubber module of the air-recirculated ventilation system is a method of cleaning air through water, the cooling effect on the same principle as a cooling pad can be expected. Meanwhile, in the case of ammonia gas, it was confirmed that the internal ammonia concentration was maintained below an appropriate level with an average of 8.12 ppm because the ammonia gas was sufficiently discharged with a high ventilation rate. This was a result similar to the internal concentration as a result of the field experiment.

3.3.2. Results of CFD Simulation for Internal Environment Improvement (Ventilation Rate and Radiator)

Figure 15 shows the computed results according to the ventilation rate and the use conditions of the radiator. The ventilation rate of 0.07 min⁻¹ in the actual ventilation rate operated in the experimental piglet house, and the minimum ventilation rate based on the MWPS according to the breeding head conditions is 0.12 min⁻¹. In the experimental piglet house, the ventilation rate was lower than the recommended ventilation rate, and accordingly, the temperature inside the piglet house can be maintained at 28 °C, but it was found that the internal ammonia concentration accumulated up to 40 ppm. However, even when operated with the recommended minimum ventilation rate of 0.12 min⁻¹, the internal ammonia concentration was about 31 ppm (Figure 15c). It was judged that it would be difficult to improve the environment inside the piglet house by operating the recommended minimum ventilation rate. Accordingly, it was attempted to predict the required ventilation rate to reduce the ammonia concentration by computing the increase in ventilation rate. The result of CFD simulations according to the ventilation rate at 0.18 min⁻¹, 0.24 min⁻¹, and 0.3 min⁻¹ showed that the internal temperature decreased to 23 °C, 21 °C, and 19 °C on average, respectively, while the ammonia concentrations were reduced from 40 ppm to 24 ppm, 19 ppm, and 15 ppm, respectively. The result confirmed that the ventilation rate should be more than 0.25 min⁻¹ to reach the allowable ammonia concentration of 20 ppm. However, since the temperature inside the piglet house was less than 20 °C, there was a limit to increasing the ventilation rate in winter. Therefore, in order to reduce the harmful gas by increasing the ventilation rate, it is necessary to supplement heat by using a heating device. The heating system was analyzed based on the actual conditions of the radiator installed in the experimental piglet house. The radiator was assumed to have a standard heat radiant value of 522 W, 600 W, and 650 W based on the heat radiant area of the radiator installed in the experimental piglet house. In the case of using the radiator, it was analyzed that at the minimum ventilation rate of 0.2 min⁻¹ at which the ammonia concentration was maintained properly, the temperature of the radiator can be maintained up to 27 °C only when the radiant value was 650 W. It is most suitable to control the internal environment by increasing the ventilation rate and the radiator to 650 W. Since the use of the radiator requires energy consumption, it is considered that the air-recirculated ventilation system is needed to control the internal environment by maximizing energy efficiency.
3.3.3. Results of CFD Simulation for Internal Environment Improvement (Ceiling Slots)

The improper design of ceiling slots can result in high ammonia gas accumulation in various locations inside the pig house when a low ventilation rate is operated. Therefore, the aerodynamic analysis of the inlet and outlet was conducted through CFD simulation, and improvement methods were evaluated by varying the conditions of ceiling slots. Table 7 shows the results of the internal average temperature and ammonia concentration according to the opening conditions of the ceiling slots. The existing ceiling slots are not installed at uniform intervals, and the #1 and #7 slots on both sides are located at abnormally narrow intervals (Figure 16). It may thus be difficult to remove harmful gas near the piglet zone because the inflow of air cannot be made uniformly. In addition, #4 is a slot located on the same line as the chimney fan, which is the location most affected when the negative pressure of the chimney fan is formed. There is a risk that the harmful gas inside the piglet house cannot be discharged and the fresh air can be immediately exhausted. In the results of Table 7, cases 1 to 3 were computed results with the same ventilation rate of 0.12 min\(^{-1}\), and cases 4 to 6 were computed results with a ventilation rate of 0.25 min\(^{-1}\). In the case of a low ventilation rate, there was no significant difference in the internal average ammonia concentration according to the condition of ceiling slots. In the case of cases 4 to 6, the ammonia concentration was reduced by about 6% depending on the ceiling slots’ opening condition, but there is no significant effect in reducing the amount of...
ammonia inside the piglet house. The ammonia concentration was greatly affected by the 
ventilation rate, whereas the internal ammonia concentration distribution was significantly 
different according to the ceiling slot conditions. When all slots were opened, fresh air from 
the corridor flowed in from #7 first, the ammonia concentration was kept low around #7, 
and the ammonia concentration increased toward the opposite side of the corridor. When 
the ventilation was operated by closing ceiling slots #6 and #7, ammonia was removed 
by inflowing fresh air to the opposite side of the corridor, but the air on the corridor side 
was not sufficiently replaced, resulting in a high ammonia concentration. Therefore, it is 
considered that it was difficult to solve the ammonia gas accumulation problem even if 
slots #6 and #7 were closed to guide the incoming air to the opposite side of the corridor. 
On the other hand, when ceiling slot #4 adjacent to the chimney fan was closed, it was 
confirmed that the ammonia concentration inside the piglet house was uniformly low. This 
is because fresh air inflowed to both ends of the piglet house so that fresh air could flow 
into the whole piglet house, and internal ammonia gas could be discharged at the chimney 
exhaust fan. Therefore, to minimize the high accumulation area of ammonia gas inside the 
piglet house, it is necessary to consider the location of the ventilation fan and the inlet. In 
addition, to reduce the concentration of ammonia gas inside the piglet house, it is important 
to improve the air exchange rate by increasing the ventilation rate.

Figure 16. Distribution of ammonia concentration inside the experimental piglet house according to 
the opening conditions of ceiling slots.
The table below presents the CFD computed results of air temperature and ammonia concentration according to the opening conditions of the ceiling slots and ventilation rate.

| No. | Variable Factors of CFD Simulation (Ceiling Slot Conditions and Ventilation Rate) | Avg Temp (°C) | Avg Ammonia (ppm) |
|-----|--------------------------------------------------------------------------------|---------------|-------------------|
| 1   | Ceiling slot (#6): closed Ventilation rate: 0.12 min⁻¹                          | 25.82         | 31.17             |
| 2   | Ceiling slot (#6, #7): closed Ventilation rate: 0.12 min⁻¹                      | 25.9          | 31.83             |
| 3   | Ceiling slot (#4): closed Ventilation rate: 0.12 min⁻¹                          | 25.57         | 31.67             |
| 4   | Ceiling slot (#6): closed Ventilation rate: 0.25 min⁻¹                          | 21.12         | 19.07             |
| 5   | Ceiling slot (#6, #7): closed Ventilation rate: 0.25 min⁻¹                      | 21.28         | 18.95             |
| 6   | Ceiling slot (#4): closed Ventilation rate: 0.25 min⁻¹                          | 20.91         | 17.8              |

3.3.4. Analysis of the Air-Recirculated Ventilation System

Even though the inside temperature is properly maintained using a low ventilation rate during the winter season using the existing ventilation, it was confirmed that the amount of ammonia concentration inside the piglet house was very high. It was also found that the ammonia concentration was properly maintained but there was a risk of high temperature stress when no cooling device was used. In this study, the air-recirculated ventilation system was used to maintain the proper environment inside the piglet house and to evaluate the applicability of the system to reduce odors and harmful gases without temperature problems. In order to evaluate the air-recirculated ventilation system, the internal temperature and ammonia concentration of the experimental piglet house were evaluated according to the ventilation rate and outdoor air mixing ratio. The removal efficiency of the ammonia gas may change depending on the configuration of the wet scrubber and the pH condition of the cleaning solution. The research team has conducted a removal efficiency test according to the conditions of the cleaning solution prior to the full operation of the system. The results revealed that utilizing an acid solution will give a removal efficiency of about 8–90% while a groundwater cleaning solution has 60% removal efficiency. Therefore, the two removal efficiencies were used as calculation conditions in CFD model. Figure 17 shows the internal temperature and ammonia concentration according to the ventilation rate (0.1, 0.2, 0.6, and 0.9 min⁻¹) and outdoor air mixing ratio when the air-recirculated ventilation system was applied. In the case of the minimum ventilation rate of 0.1 min⁻¹, the air-recirculated ventilation system was not used, and the outdoor air mixing ratio was set to 100%. As a result of CFD calculation, it was predicted that the ammonia gas environment would be poor when the air-recirculated ventilation system was not used, with an internal temperature of about 28 °C and an ammonia concentration of 40 ppm due to the low ventilation rate (Figure 17a). In the case of using the air-recirculated ventilation system, the temperature of the incoming air was higher than the external air, with the advantage that the temperature inside the piglet house did not decrease rapidly. Therefore, it is possible to reduce the internal ammonia concentration by increasing the ventilation rate, and it is judged that the internal environment of the piglet house can be improved by appropriately controlling the ventilation rate and the outdoor air mixing ratio.
Figure 17. CFD computed results of temperature and ammonia concentration inside the experimental piglet house according to the ventilation rate and outdoor air mixing ratio using an air-recirculated ventilation system.

(a) Air temperature near the piglet zone when using air scrubber

(b) NH₃ concentration near the piglet zone when using air scrubber (90%)

(c) NH₃ concentration near the piglet zone when using air scrubber (60%)

Figure 17. CFD computed results of temperature and ammonia concentration inside the experimental piglet house according to the ventilation rate and outdoor air mixing ratio using an air-recirculated ventilation system.
When the ventilation rate was increased to 0.2 min$^{-1}$, the internal temperature of the piglet house was maintained at an appropriate level when all 25, 50, and 75% outdoor air mixing ratios were applied. As the mixing ratio of the outdoor air increases, the air temperature near the piglet zone can be lowered. However, when operating the ventilation rate of 0.2 min$^{-1}$, even if 75% of the external air was mixed, the temperature of the remaining 25% of the recirculated air was high, so it was possible to maintain the appropriate level of temperature inside the piglet house. On the other hand, when the ventilation rate and mixing ratio were increased, the inflow of the external air increased. This resulted in the air temperature decreasing to 25 $^\circ$C inside the piglet house. Therefore, it is necessary to control the ventilation rate at 0.2 to 0.6 min$^{-1}$ and to maintain the temperature properly by controlling the outdoor air mixing ratio of the air-recirculated ventilation system in real time.

The ammonia concentration was analyzed according to the ventilation rate, external-air-mixing ratio, and removal efficiency (Figure 17b,c). When the ventilation rate was operated at 0.2 min$^{-1}$ in the experimental piglet house, the internal ammonia concentration was reduced but still did not reach the allowable concentration of 20 ppm, although the removal efficiency was 90%. When the ventilation rate was increased to 0.6 min$^{-1}$, the ammonia concentration was maintained at an appropriate concentration level. This was because the amount of air cleaned in the wet scrubber module increased with the increase in fresh external air. There was no significant difference in ammonia removal when the ventilation rate was increased further. The appropriate ammonia concentration could be maintained because the ventilation rate was sufficient compared to the ammonia generation rate inside the piglet house. On the other hand, as the ventilation rate and external-air-mixing ratio are increased, the internal temperature can be lowered. Therefore, the wet scrubber with a removal efficiency of 90% can maintain an appropriate environment with a ventilation rate of 0.6 min$^{-1}$ and an external-air-mixing ratio of about 25%. In actual operation, it is possible to reduce the carbon dioxide that cannot be removed using the wet scrubber module by controlling the outdoor air mixing ratio according to the outdoor weather conditions.

In the condition of the removal efficiency of 60%, the ammonia concentration condition was not satisfied at the ventilation rate of 0.2 min$^{-1}$. However, as the ventilation rate and outdoor air mixing ratio increased, the internal ammonia concentration could be maintained below the allowable concentration (20 ppm). Since the amount of ammonia removed was smaller than when the removal efficiency was 90%, the ammonia removal according to the outdoor air mixing ratio showed a greater effect. However, if the ventilation rate was sufficiently increased, the internal ammonia concentration could be maintained at 10–15 ppm. Therefore, it is expected that the temperature and ammonia gas environment inside the piglet house can be optimally maintained through the air-recirculated ventilation system if the ventilation rate and outdoor air mixing ratio are properly operated according to the removal efficiency and outdoor weather conditions.

4. Conclusions

In this study, the main problems of the internal environment inside the pig house were identified through the field experiments and CFD simulation of the experimental piglet house. The accuracy and computational efficiency of the CFD model were validated based on the field measurement data, and case studies were conducted based on the validated CFD model. Based on the CFD computed results, various aerodynamic analyses were conducted according to various conditions such as outdoor weather conditions, the ventilation rate, and inlet types. In addition, by applying the air-recirculated ventilation system to the developed CFD model, the suitability of the air-recirculated ventilation system was evaluated according to the ventilation rate, outdoor air mixing ratio, and removal efficiency.
The result of the field experiment showed that the maximum ventilation rate during the high temperature period was increased in summer with a high of about 33 °C. During this period, it was found that the ventilation rate was not sufficiently increased, and the gas environment was not properly maintained. To maintain the internal air temperature in winter, it was found that less than the recommended minimum ventilation rate was operated, resulting in an unsuitable gas environment with an ammonia gas concentration of above 40 ppm.

Through CFD simulation, the main problems that occurred due to the ventilation rate and inlet types of the experimental piglet house were identified. To reduce the high gas concentration environment, it was essential to increase the ventilation rate. The result of analysis according to the use of the radiator showed that it is possible to properly maintain the internal gas when the ventilation rate was increased by operating the radiator at 630 W or more. For the uniformity inside the experimental piglet house, the inlet conditions of the ceiling slots were analyzed. It was also found that the location of the ceiling slots in the experimental piglet house was not appropriate. It was confirmed that the internal uniformity could be improved by preventing direct flow to the chimney exhaust fan by closing the center (#4) of the ceiling slots.

Finally, the usability of the air-recirculated ventilation system was evaluated to improve the existing problems based on the developed CFD model. Compared to the existing ventilation system, the ventilation rate can be increased by about four times or more, and it was found that if the ventilation rate and outdoor air mixing ratio are automatically controlled according to the outdoor environment and removal efficiency conditions, the growth environment inside the piglet house can be maintained properly. Additionally, it has the advantage of reducing harmful gases discharged outside and preventing diseases.

Meanwhile, one of the parts that cannot be considered in this CFD simulation was the internal carbon dioxide concentration. Since the carbon dioxide does not dissolve well in water, the air-recirculated ventilation system cannot remove carbon dioxide, so if carbon dioxide is not sufficiently discharged, it may cause abnormalities in the respiratory and circulatory systems of piglets. Considering this, it is necessary to properly maintain the gas environment by controlling the outdoor-air-mixing ratio in real time.

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