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Development of a Simulation Model for a Ventilation System for Swine Confinement

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ABSTRACT

The objective of this study is to develop a simulation model of a ventilation system for a modern swine confinement. The confinement is divided into two zones: the room where the pigs reside and the pit that stores the waste. Two fans located in the side wall of the room and one fan located in the end wall of the pit are used to control the indoor air quality (IAQ) within the confinement. IAQ in this study addresses thermal and pollutant factors. For each zone, the conservation of mass and energy equations are written. The conservation of mass equations apply for dust, ammonia, and water vapor concentration. The conservation of energy describes the air temperature of the zones. The equations contain heat generation terms for thermal energy due to lights, heaters, and pigs, and mass source terms due to dust, water vapor, and ammonia. Relations for the generation terms are presented. An icon-based software is used to solve the system of equations that represent the IAQ models. Results of temperature, humidity, and concentrations of ammonia and dust are obtained from the simulation model under different conditions. By successfully examining the example cases, further investigations are warranted on larger-scale models having more complexity, components, control algorithms, and applications.

KEYWORDS: Simulation, Ventilation, Swine, Indoor Air Quality

INTRODUCTION

Because experiments in actual buildings are difficult and costly to undertake, it is attractive to develop simulation models of the real system. Simulation models would enable studies to be conducted on ventilation rates, heating requirements, etc. A limited number of measurements then would be required to validate the models. Axaopoulos et al. (1992) developed a computer simulation model to predict the air temperature and relative humidity inside a swine unit by using a computer program based on a modular approach (TRNSYS, 1981). Another simulation tool that has emerged within the past few years is Simulink (Simulink, 1998) built into Matlab (Matlab, 1999). Simulink is an icon-driven simulation tool for dynamic analysis of physical systems. Other software packages similar to Simulink exist, such as Xmath (Xamth, 1999) and Easy5 (Easy5, 1998). In this study, Simulink is chosen to solve the models for the ventilation system because of its accuracy and convenience for the user to construct the model (Zhang et al., 1999).

The indoor environmental parameters, especially temperature and humidity, of swine confinements are primarily controlled by ventilation (Donham et al., 1989). During winter months, the air flow requirements are based on the need to maintain relative humidity (RH) and temperatures in a confinement near levels conducive to the health and growth of pigs. Humidity increases in confinements from animal respiration, which can be controlled by circulating dry air vented into the building (Murphy et al., 1991). In some cases, depending on the severity of the winter, body heat from animals in the confinement is sufficient to maintain temperatures above 1.7°C. However, in colder climates, some form of supplemental heat is required. During the summer months, the main environmental consideration involves high temperatures that result in overheated pigs. During that time, completely enclosed buildings rely on increasing ventilation rates to over 10 times winter rates ("Finishing" pigs weighing between 68 to 100 kg require approximately 0.0047 m^3/s per animal in the winter compared to 0.057 m^3/s per animal in the summer (Murphy et al., 1991)).

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Both numerical simulations and pilot-scale evaluations of livestock building ventilation systems have been performed to estimate the spatial variability and relative amounts of airborne contaminants in these buildings. Assessment of the spatial variability in swine confinements has been generally performed by numerical simulation (Breum et al., 1990; Hoff and Bundy, 1996; Liao and Feddes, 1992; Maghirang et al., 1994). These models rely on partial differential equations that describe the advective and diffusive contaminant transport processes that govern the relationship between the amount of a contaminant in a certain location and the movement of air caused by the ventilation system configuration (Hoff and Bundy, 1996). These models have been used to determine the influence of airflow patterns on both gas (Breum et al., 1990) and particle distributions (Liao and Feddes, 1992; Maghirang et al., 1994) Factors that have been found to influence airflow patterns include configuration of the ventilation system, design and area of the inlet vent, ventilation rates, temperature and humidity of the incoming air, heat and moisture production of the animals, and building characteristics, such as size and enclosure design (Maghirang et al., 1994). Because small particles (Dia. < 5 µm) have a very low settling velocity, they are assumed to follow air motion, and hence similar factors may affect their transport as well (Breum et al., 1990; Hoff and Bundy, 1996; Liao and Feddes, 1992; Maghirang et al., 1994). In one of the few studies to demonstrate the spatial variability of airborne contaminants in an actual swine confinement (Maghirang et al., 1997), results indicate that total dust concentrations varied significantly between air volumes directly over the animal pens and volumes over the central service alley. However, the same study concluded that respirable dust concentrations did not vary significantly with sample location.

METHODS

A simulation model for a swine confinement located on the Kirkwood Community College in Cedar Rapids, Iowa was developed. The building parameters are tabulated in Table 1. Air exchanges between the room and pit was considered (Nicas, 1996).

The governing equations describing the system are derived from statements of the conservation of energy and mass as applied to a control volume. All conservation equations are of the form

$$\frac{dE_{cv}}{dt} = E_{in} - E_{out} + E_{gen} \tag{1}$$

where E_{cv} represents the conservative quality considered. The term on the left is the rate of increase of E within a control volume. E_{in}, E_{out}, and E_{gen} denote the incoming, outgoing and generated amount of E. In all equations, E_{cv} is assumed to be uniform within the control volume. In the models developed here, E is expressed in terms of properties and a flow rate or a volume. It is assumed that the values of the properties leaving the control volume are equal to those in the control volume. The models for the room and pit are:

<u>Energy model for room and pit</u>

$$\begin{aligned}\rho_a V_r c_a \frac{dT_r}{dt} = {} & \rho_a Q_o c_a T_o - \rho_a Q_1 c_a T_r - \rho_a Q_2 c_a T_r - \rho_a Q_p c_a T_r - U_{rw} A_{rw} (T_r - T_o) \\ & + U_{pr} A_{pr} (T_p - T_r) - \rho_a Cir\, Q_p c_a T_r + \rho_a Cir\, Q_p c_a T_p + q_{gen}\end{aligned} \tag{2}$$

Table 1. Buildings and animal parameters used in the simulation.

Dimension (m)	**Room**	**Pit**
Width	7	7
Length	9	9
Height	2.4	0.9
Heat transfer coefficient (W/m²-K)		
Room walls	3.3	
Room floor	3.3	
Pit walls	3.3	
Animal parameters		
Pig weight(kg)	180	

Number of pigs	10

$$\rho_a V_p c_a \frac{dT_p}{dt} = \rho_a Q_p c_a T_r - \rho_a Q_p c_a T_p - U_{pw} A_{pw} (T_p - T_o) - U_{pr} A_{pr} (T_p - T_r) - \rho_a CirQ_p c_a T_p + \rho_a Cir Q_p c_a T_r \quad (3)$$

where

ρ_a Density of air (kg/m^3)
c_a Specific heat of air (J/kg-K)
Q_o Total air flow rate (m^3/s)
Q_1 Flow rate of first wall fan (m^3/s)
Q_{1p} Flow rate of pit fan (m^3/s)
A_{pr} Area of the floor (m^2)
Cir Air exchange coefficient
V_p Pit volume (m^3)
V_r Room volume (m^3)
T_r Room temperature (K)
T_o Outdoor air temperature
Q_2 Flow rate of second wall fan (m^3/s)
A_{rw} Side wall area of room (m^2)
T_p Pit temperature (K)
q_{gen} Heat generation in the room (W)
A_{pw} Side wall area of pit (m^2)
U_{rw} Overall heat transfer coefficient of side walls of room (W/m^2-K)
U_{pr} Overall heat transfer coefficient of floor between room and pit (W/m^2-K)
U_{pw} Overall heat transfer coefficient of side walls of pit (W/m^2-K)

The heat generators include heaters, lamps, and pigs heat production. Cir is used to account for the possibility that air from the pit may find its way to the room.

Humidity model for room and pit

$$\rho_a V_r \frac{d\omega_r}{dt} = \rho_a Q_o \omega_o + \rho_a Cir\, Q_p \omega_p - (Q_1 + \dot{Q_2} + Q_p)\rho_a \omega_r - \rho_a Cir\, Q_p \omega_r + G_{hr} \quad (4)$$

$$\rho_a V_p \frac{d\omega_p}{dt} = \rho_a Q_p \omega_r + \rho_a Cir\, Q_p \omega_r - \rho_a Q_p \omega_p - \rho_a CirQ_p \omega_p + G_{hp} \quad (5)$$

where

ω_r Room air humidity ratio (kg w.v./kg d.a.)
ω_o Outside air humidity ratio (kg w.v./kg d.a.)
G_{hp} Water vapor production in pit (kg/s)
ω_p Pit air humidity ratio (kg w.v./ kg d.a.)
G_{hr} Water vapor production in room (kg/s)

The notation of w.v. and d.a. denotes water vapor and dry air. Water vapor production in the room is caused by the pig respiration. In the pit, the evaporation of liquid water from the manure surface adds to the water vapor of the air flowing in the pit.

Dust model for room and pit

$$V_r \frac{df_r}{dt} = Q_o f_o + Cir\, Q_p f_p - (Q_1 + \dot{Q_2} + Q_p) f_r - Cir\, Q_p f_r + G_{dr} \quad (6)$$

$$V_p \frac{df_p}{dt} = Q_p f_r + CirQ_p f_{dr} - \dot{Q_p} f_p - CirQ_p f_p + G_{dp} \quad (7)$$

where

f_r Dust concentration in room (kg/m^3)
f_p Dust concentration in pit (kg/m^3)
G_{dp} Dust production in pit (kg/s)
f_o Outside dust concentration (kg/m^3)
G_{dr} Dust production in room (kg/s)

The generation rates of dust were obtained based on measurements in the confinement.

Ammonia model for room and pit

$$V_r \frac{dC_r}{dt} = Q_o C_o + Cir\, Q_p C_r - (Q_1 + Q_2 + Q_p) C_r - Cir\, Q_p C_p + 0.7144\, G_{ar} \quad (8)$$

$$V_p \frac{dC_p}{dt} = Q_p C_r + Cir\, Q_p C_r - Q_p C_p - Cir\, Q_p C_p + 0.7144\, G_{ap} \quad (9)$$

where

C_r Ammonia concentration in room (ppm)

C_o Outside ammonia concentration (ppm)

C_p Ammonia concentration in pit (ppm)

G_{ar} Ammonia production in room (mg/s)

G_{ap} Ammonia production in pit (mg/s)

The generation rates of ammonia were obtained based on measurements in the confinement.

Since ppm is the unit of the ammonia concentration used in the experiment, the conservation of mass equation was expressed in terms of the concentration with the units of ppm. To maintain the units consistent, G_{ar} is multiplied by 0.7144 according to the following derivation.

The unit conversion for gases is given by

$$mg / m^3 = \frac{ppm \cdot M}{0.08205 \cdot T}$$

where M is molecular weight of the gas with the units of g/mol and T is the gas temperature with the unit of K. The ammonia M is 17g/mol and its temperature is assumed to be 290K. Inserting the values to the formula above , the conversion factor becomes

$$mg / m^3 = 0.7144\, ppm$$

The unit of mg/s can be written as $\frac{mg \cdot m^3}{m^3 \cdot s}$ and converted to 0.7144 ppm m^3/s.

The system of equations in Eqs. (2) to (9) were solved using the icon-based software Simulink (1998).

RESULTS AND DISCUSSION

The model was exercised for various cases to show that it was working properly. For some values of the governing parameters, such as Cir = 0, analytical solutions of the model equations are possible. The numerical results from the model for these parameters were compared to the results from the analytical solutions. In all comparisons, excellent agreement was found between the two results.

Input parameters were modified for each case to emphasize certain aspects of the model. In Case1, all the components worked at their maximum power. Table 2 shows the values used in Case 1. The values are similar to those for the real system. Compared with Case 1, a parameter value is changed each time from Cases 2 to 6 to focus on a different aspect of the model. The description of these cases is described in Table 3.

Figures 1 to 4 show the indoor temperatures, humidity ratios, ammonia concentrations, and dust concentrations for different cases. Figure 5 shows the outdoor temperature for 24 hours a day. The whole-day outdoor temperature is simulated according to the assumption that the lowest temperature appeared at 4:00 am, the highest temperature at 4:00 pm, and the temperature varies in a sine-wave fashion. The results show that the indoor temperature in sine-wave fashion just as the outdoor temperature. Because of the heat generation within the room, the indoor temperature is higher than the outdoor temperature. Since the generation of the humidity, ammonia, and dust are constant, the values of indoor humidity ratios, ammonia concentrations, and dust concentrations are constant after some time. The results for the humidity ratios, ammonia concentrations, and dust concentrations reach steady-state values within about 1000 s after the start of the simulation.

As expected, the results also show that the indoor temperature decreases when the heat generation decreases, the humidity ratio increases when the humidity generation increases, the ammonia concentration increases when the ammonia generation increases, and the dust concentration increases when the dust generation increases, which all seemed reasonable. The results also show that when the air exchange coefficient between the room and pit increases, the

Table 2 Numerical values of model parameters in case 1.

Symbol	Unit	Current value
ρ_a	kg/m^3	1.225
c_a	J/kg-K	1005.4
q_p1:Heat generation per pig	W	594
q_L1:Heat generation per lamp	W	125
N_{lamp}:Number of lamps	N/A	10
$Q1_{max}$:Max. flow rate of first wall fan	m^3/s	2.07
$Q2_{max}$:Max. flow rate of second wall fan	m^3/s	2.07
$Q3_{max}$:Max. flow rate of pit fans	m^3/s	0.9
C_o	ppm	0
f_o	mg/m^3	0
G_{hr}	kg/s	0.0012
ω_o	kg w.v/ kg d.a	0.011

Table 3 Simulation cases.

Case	Testing	Q_{heater} (W)	G_{hup} (kg/s)	G_{ap} (mg/s)	G_{dr} (mg/s)	Cir
1	base	17,400	0.046	21.6	3.024	0.1
2	temperature	8,700				
3	humidity		0.138			
4	ammonia			64.8	9.072	
5	dust					
6	system					0.8

ammonia concentration in room and pit become closer. This means that more ammonia is transferred from the pit to the room, which may be harmful to the workers and pigs.

CONCLUSIONS

A set of equations was developed for an IAQ model of a ventilation system that is comprised of three fans, a room, and a pit, and is used to study the ventilation requirements for a modern swine confinement. Application of real values of the parameters allows the model to calculate and display the indoor air temperatures, humidity ratios, ammonia concentrations, and dust concentrations in the room and pit. The numerical values from the model are produced using an icon-based software package. Use of the IAQ model frees the user of solving the coupled equations and allows a visual display of the interconnections from one component to another. The model can be used to examine the effects of different control scenarios on the IAQ of the confinement.

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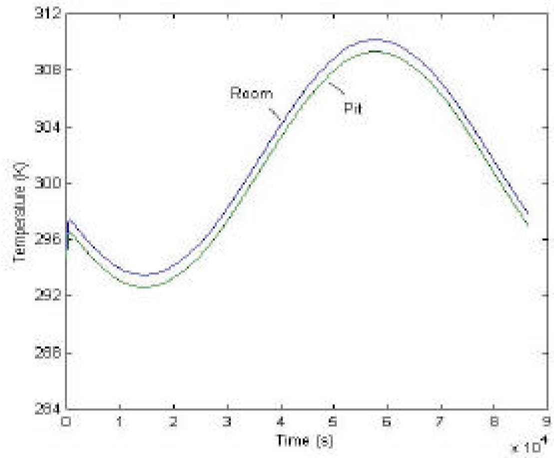
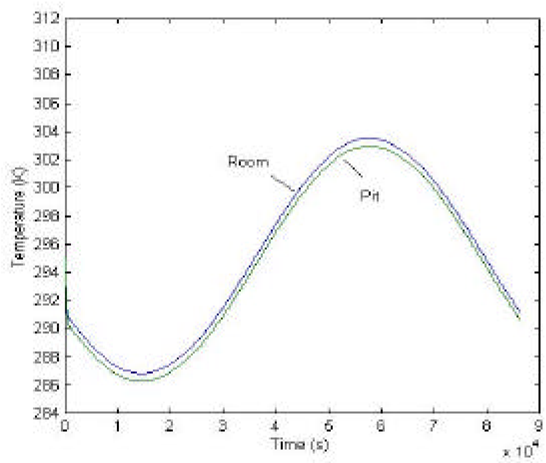
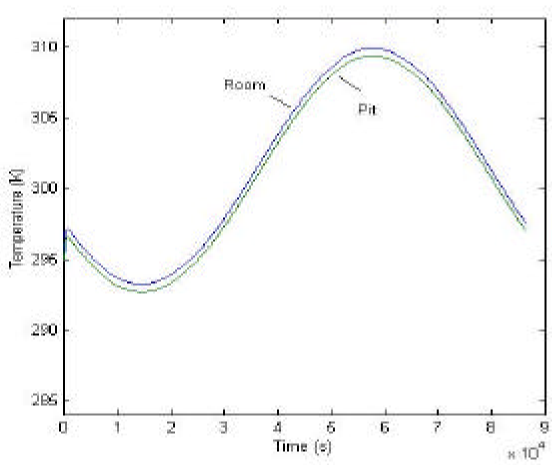


(a) Indoor temperature in Case 1.

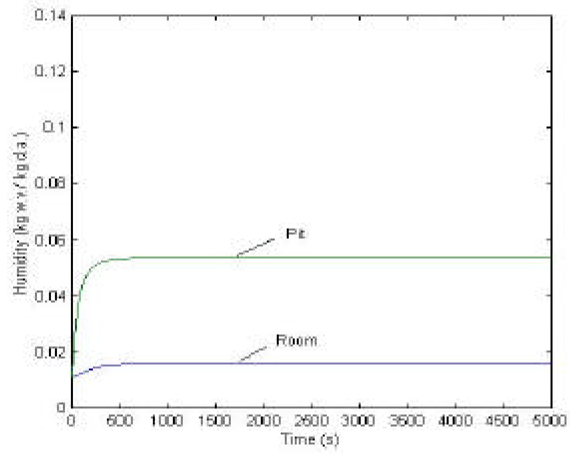


(b) Indoor temperature in Case 2.

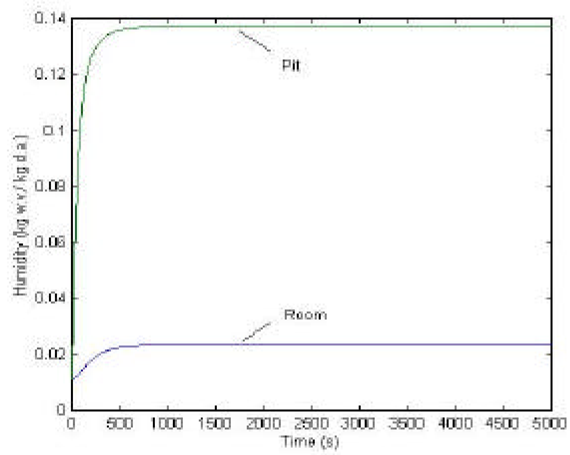


(c) Indoor temperature in Case 6.

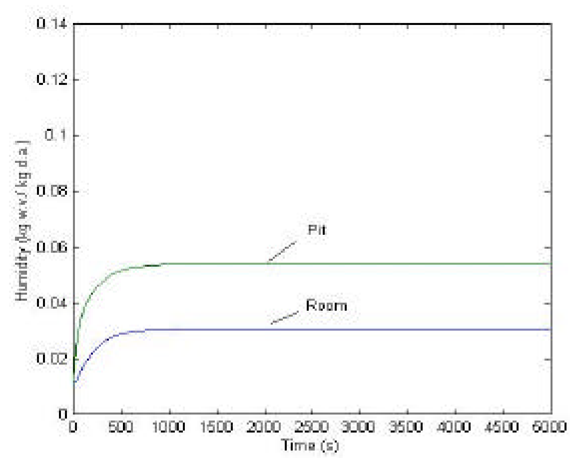
Figure 1 Results for indoor temperature.



(a) Humidity ratio in Case 1.

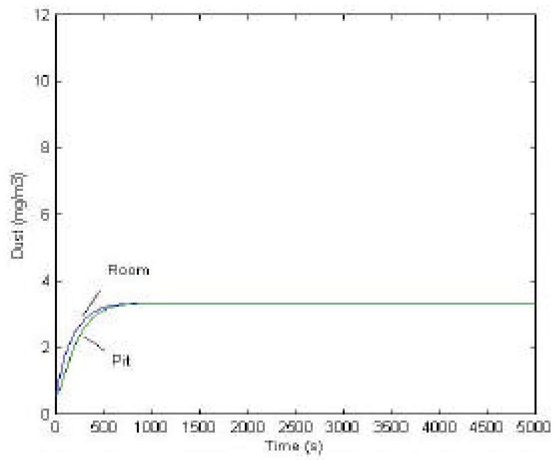


(b) Humidity ratio in Case 3.

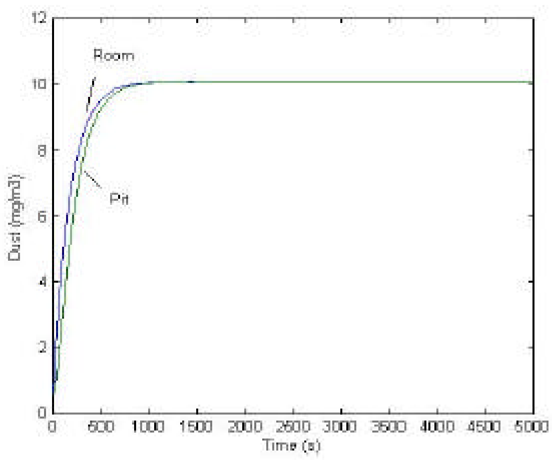


(c) Humidity ratio in Case 6.

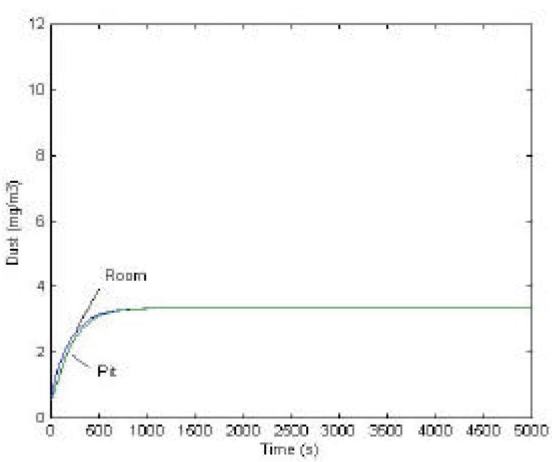
Figure 2 Results for humidity ratio.



(a) Dust concentration in Case 1.

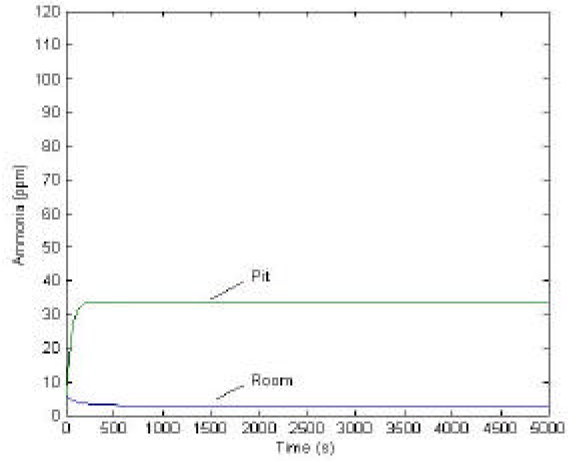


(b) Dust concentration in Case 4.

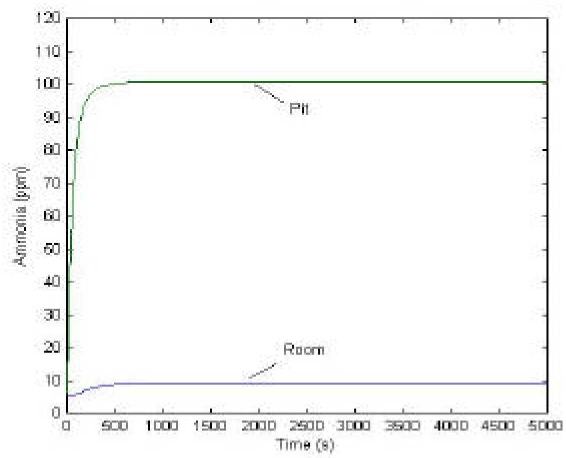


(c) Dust concentration in Case 6.

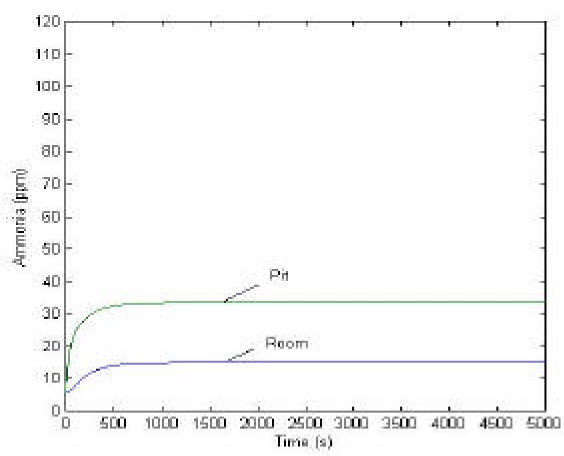
Figure 3 Results for dust concentration.



(a) Ammonia concentration in Case 1.



(b) Ammonia concentration in Case 5.



(c) Ammonia concentration in Case 6.

Figure 4 Results for ammonia concentration.

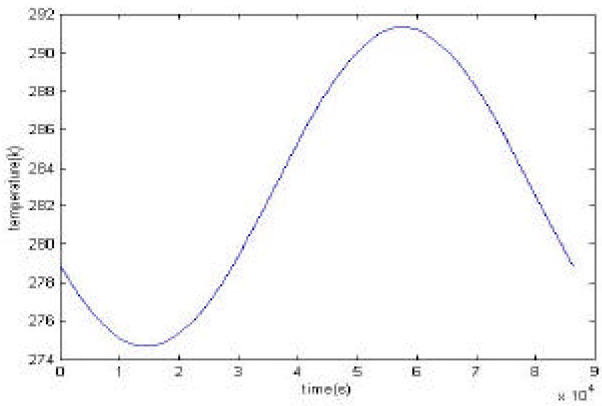


Figure 5 Outdoor temperature for all cases.

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