Development of a Simulation Model for

a Ventilation System for a Swine Building

L. Zhang, T. F. Smith, P. T. O'Shaughnessy

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Abstract. The objective of this study was to develop a simulation model of a ventilation system in a modern swine building used for farrowing pigs. The building was divided into two zones: the room where the pigs reside and the pit that stores the waste. In addition to a space heater and lamps, two fans located in the side wall of the room and one fan located in the end wall of the pit were used to control the indoor temperature. A differential equation expressing the conservation of energy was written for each zone. The room equation contained heat generation terms to account for thermal energy due to lights, heaters, and pigs. Control strategies based on an actual controller in the room were developed to activate the heaters, lights, and fans to maintain room temperature at a setpoint. An icon-based software was used to solve the system of equations that represent the model. The model was validated by comparing numerical and experimental results. By systematic adjustment of a limited number of model parameters, the model results are in agreement with the experimental data.

Keywords. Simulation, Ventilation, Swine

INTRODUCTION

A large increase in the number of highly concentrated hog production facilities has been evident in recent years. A typical swine building contains pens on either side of a central corridor. The number of pens per side determines the overall length of the building. Modern swine buildings are built with an open-slatted floor so that animal waste can be collected in a pit below the floor. These buildings are typically ventilated in the winter with the use of a fan located at the long end of the building and pulling air directly from the pit area. Air is drawn through slots in the eaves of the roof, across the attic space, down through vents along the sidewall of the room, and finally through the slots in the floor before being exhausted by the pit fan. This design allows for pre-warming the incoming air and ventilating the pit area. If a building is entirely mechanically ventilated, additional exhaust fans are often placed on an exterior sidewall of the building to pull additional air out of the room to aid in cooling during the summer (Murphy et al., 1991). Buildings used to house farrowing sows are typically of this type.

The indoor environmental parameters of temperature and humidity for swine confinement buildings are primarily controlled by ventilation (Donham et al.,1989). During winter months, the airflow requirements are based on the need to maintain the relative humidity and temperature near levels conducive to the health and growth of pigs. Humidity increases in confinement buildings from animal respiration and wastes and can be controlled by circulating drier air vented into the building. During the summer months, the main environmental consideration involves high temperatures that may result in overheated pigs. During that time, completely enclosed buildings rely on increasing ventilation rates to over 10 times winter rates (Murphy et al., 1991). Because of the importance of providing adequate ventilation, it is necessary to study and develop efficient ventilation systems and control strategies in swine confinement buildings.

Two techniques can be used to study control strategies developed for ventilation systems. One is to conduct field experiments and the other is to develop simulation models. Because experiments in actual buildings are difficult and costly to undertake, and as computers and software become faster and more powerful, simulations are an attractive alternative to field studies. Computer simulations use physically-based mathematical equations to model the system and components. Once the simulation model has been validated with experimental data, it can be used to simulate a wide variety of changes in the system much easier and faster than an experiment of a real situation.

Axaopoulos et al. (1992) developed a model to simulate the thermal environment of growing pigs. The model is used to predict the air temperature and relative humidity inside a swine unit. The outside climatic conditions were for summer conditions. Information about the ventilation control is missing, and the simulation results were not compared with actual data. In a later study (Axaopoulos et al., 1994), the same model was used to simulate a growing-finishing building under January climatic conditions. The model was also used to simulate a misting control strategy and to evaluate the effect of misting on the inside dry-bulb temperature and relative humidity (Panagakis et al., 1996). By using a dynamic thermal environmental model for livestock buildings, Zhang and Barber (1993) simulated variable ventilation rates, temperature and relative humidity responses, and supplemental heat consumption. A simulation model of a ventilation system for a modern swine confinement was developed by Zhang et al., (2001) to study indoor air quality. However, the model does not include the control strategies for the equipment.

The well-mixed room model is traditionally used to predict the temperature and humidity in indoor environments. However, real-world rooms tend not to be perfectly mixed (Nicas, 1996) in which case a two-zone model would better describe the room concentration profile than would the well-mixed room model. The two-zone model assumes the air within each zone to be considered perfectly mixed, and introduces an air exchange rate between the zones (Nicas, 1996). A model predicting vertical temperature distribution in a large space (Togari et al., 1993) used similar concepts applied to multiple zones. In that model, the space is vertically divided into a number of zones. The model evaluates descending (or ascending) currents and the heat transfer caused by the temperature difference between vertically adjacent zones.

The review of the pertinent literature shows that limited research has been conducted to develop simulation models for enclosed swine buildings. Furthermore, little work has been reported to design energy-efficient control strategies of ventilation systems for the purpose of maintaining appropriate indoor environments in swine buildings. Additional research is warranted to develop models that predict the environmental conditions in swine buildings and control strategies that maintain acceptable values of the environmental parameters for a swine building.

The study objectives were (1) to develop a simulation model of a ventilation system as it affects indoor temperature for a modern swine building by introducing actual parameter values into the model and (2) to validate model results by comparison with experimental data. To carry out these objectives, an energy conservation model was developed and implemented. Actual parameters associated with the conditions existing in a working swine building were used as inputs to the model. To control events such as fan and heater operations, a controller representing the actions programmed in an electronic controller governing the temperature control devices in the building is included in the model. The model was validated by comparison with real-time data collected at the study site. Certain parameter values were varied in a systematic procedure to obtain a better association between the model and experimental data.

To simplify the description of the model development process and recognizing that the room temperature is the only input for the actual controller, the indoor temperature is modeled and compared with actual data here. However, concurrent research (Zhang et al., 2001) is addressing the inclusion of indoor relative humidity and the two important indoor air contaminants, airborne dust and ammonia, into an overall model. In a manner similar to that described below, these important indoor air quality (IAQ) parameters are described by differential equations expressing the conservation of mass of each parameter and added to the simulation model. A subsequent paper will address results from that portion of the research with the goal of demonstrating the use of simulation to indicate the effect of various ventilation strategies on IAQ.

Model Description

System Description

A swine building located on the campus of the Kirkwood Community College in Cedar Rapids, Iowa was simulated in this project. Although the numerical values of the model parameters apply to this particular building, it is expected that the model can be applied to other buildings by appropriate adjustment of the numerical values. The building was used for farrowing pigs and was entirely mechanically ventilated. The building was composed of two symmetric and separate zones of which one was used as the basis of the simulation model. A zone was divided into two control volumes representing the main room where the pigs reside and the pit that stores the waste. An open-mesh floor grating between the room and pit allowed air to move between the two zones. The room contained 10 pens, 5 on each side of a central isle. To provide ventilation, there were two fans located in the exterior sidewall of the room and one fan located in the end wall exhausting air from the pit. A water sprinkling system was available for additional cooling in hot weather conditions that turned on after all the fans were at maximum speed and the room temperature was still high. A space heater was located in the room to provide heat in the winter. A heat lamp was available in each pen to provide extra heat in cold weather.

Energy Model

Equations that describe the energy transfer in each control volume of the building were derived from the statements of the conservation of energy. These equations were developed under the following assumed conditions: (1) thermophysical properties are constant; (2) temperatures in each control volume are uniform; (3) air exchanges between the room and the pit through recirculation; (4) kinetic and potential energies are neglected; (5) thermal and solar radiation are neglected; (6) walls have no thermal storage; and (7) the operating equipment has no time delay. The assumption of uniform temperature within a control volume is expected to be applicable because of the mechanical ventilation.

The conservation of energy equations for the room and pit are

$$\rho_a V_r c_a \frac{dT_r}{dt} = \rho_a Q_t c_a T_o - \rho_a Q_1 c_a T_r - \rho_a Q_2 c_a T_r - \rho_a Q_p c_a T_r - U_{rw} A_{rw} (T_r - T_o) - U_{pr} A_{pr} (T_r - T_p) - \rho_a C_{ex} Q_p c_a T_r + \rho_a C_{ex} Q_p c_a T_p + q_{gen} \tag{1a}$$

$$\rho_a V_p c_a \frac{dT_p}{dt} = \rho_a Q_p c_a T_r - \rho_a Q_p c_a T_p - U_{pw} A_{pw} (T_p - T_o) - U_{pr} A_{pr} (T_p - T_r) - \rho_a C_{ex} Q_p c_a T_p + \rho_a C_{ex} Q_p c_a T_r \tag{1b}$$

The initial conditions applied to these equations are: $T_r(0) = T_{r0}$, and $T_p(0) = T_{p0}$, where T_{r0} and T_{p0} are the initial temperatures for the room and pit.

The unit for each term in these equations is Watts. The left term in Equation 1a is the rate of increase of thermal energy of air in the room, and the first term on the right is the thermal energy that enters the room from the outside. The second to fourth terms are the thermal energies that leave the room through the two wall fans and the floor. The fifth and sixth terms are the heat transfer from the room to the outside and from the room to the pit. The seventh and eighth terms are the thermal energies that leave the room and reenters the room due to air recirculation between the room and pit. The air exchange coefficient, C_{ex}, is used in these terms to account for the possibility that air from the pit may find its way back to the room. This variable is given a value between 0 and 1, where 0 indicates no air recirculation between the room and pit.

The last term in Equation 1a, q_{gen}, describes the total heat generation in the room. The total heat generation in the room is the sum of the heat generation from the space heater, q_h, lamps, q_l, and pigs, q_p and is evaluated from

$$q_{gen} = q_h + q_l + q_p \tag{2}$$

where, q_h and q_l were considered equal to their electrical powers. The value of q_p was determined under the assumption that the total heat loss of an animal is directly proportional to body weight (Scott et al., 1983). The effect of misting is not included in the model.

Equation 1b is similar to Equation 1a except there is no heat generation term. The left term in Equation 1b is the rate of increase of thermal energy in the pit. The first term on the right is the energy that enters the pit from the room. The second is the energy that leaves the pit through pit fan. The third and fourth terms are the heat transfers from the pit to the outside and from the pit to the room. The fifth and sixth terms are the energies that leave or enter the pit due to the air recirculation between the room and pit.

To determine the operation of the heater, lamp, and fans, a control strategy is needed. The control strategy is discussed next.

Control Strategies

An electronic controller (Varifan, 1996) was used in the actual room to control the heater and fans relative to a setpoint temperature level. The heating/cooling control strategies of the controller are shown in Figure 1. The horizontal axis of Figure 1 is the difference between the room and setpoint temperatures. This difference is used to control the operation of the equipment. The vertical axis shows the operation conditions of the two wall fans, the pit fan, the heater, and the lamps relative to the temperature difference. Values on the vertical axis represent percent of maximum output. Although specific numerical values are cited for the control parameters, the controller and controller submodel for the simulations allow these parameters to be assigned by the user.

As shown in Figure 1, the pit fan is a variable speed fan that operates between a minimum speed (typically 60 percent of maximum) when temperatures fall below the setpoint and its maximum speed when temperatures rise by more than 1.4°C (2.5°F) above the setpoint. Wall fan 1 is a variable speed fan that, when running, operates in a linear fashion between a minimum (typically 55 percent of maximum) and maximum speed. Wall fan 1 is activated when the temperature rises to 1.4°C (2.5°F) above the setpoint, and reaches a maximum speed when the temperature rises to 2.8°C (5°F) above the setpoint. At this temperature, wall fan 2, which is an on-off fan, is turned on so that all fans are running at maximum speed when the room air temperature is 2.8°C above the setpoint. If the room temperature falls below 1.1°C (2°F) of the setpoint temperature, the heater is turned on. In the actual room, the heat lamps are turned on manually for about the first week of the piglets' birth then turned off. In the model, the lamps were set to turn on when the temperature falls below 2.2°C (4°F) from the setpoint temperature.

To prevent the heater and wall fan from switching off and on as the temperature fluctuates around their activation temperatures, "dead bands" are included in the controller. For example, as shown in Figure 1, wall fan 2 is turned on when the temperature rises to 2.8°C (5°F) above the setpoint, but shuts off when it cools to within 1.7°C (3°F) above the setpoint. Likewise, the heater turns on when the temperature falls to 1.1°C (2°F) below the setpoint, but shuts off when the temperature warms to the setpoint. The lamps have a similar "dead band" as the heater. In Figure 1, the lines with arrows illustrate the dead bands for the wall fan 2, heater, and lamp.

Model Implementation

An icon-based simulator, Simulink (Simulink, 1999), was used to implement the numerical model. Simulink is a software package for modeling, simulating, and analyzing dynamic systems. It provides a graphical-user interface for building models as block diagrams, using click-and-drag mouse operations.

As an example of how the energy models (Equations 1a and 1b) were implemented in Simulink, the first-order-ordinary-differential equation of the form

$$A\frac{dy}{dt}=B(y-y_i)+C \tag{3}$$

is discussed. y represents a temperature in the room or pit, and y_i the setpoint temperature. A represents the thermal capacitance of a control volume, B accounts for heat transfer with the environment through the building walls and the thermal exchange with the environment via the air ventilation, and C denotes the generation terms. The equivalent Simulink diagram is displayed in Figure 2. Starting at the output of the integrator icon, y_i is subtracted from the output of the integrator, y, using a summation icon. Then, the output from the summation icon is multiplied by B using a product icon. Next, the output of the product icon is added to C using a summation icon, and the output from the summation icon is divided by A using a product icon. The loop is completed by connecting the output of the product icon to the input of the integrator icon. The results can be shown by using display icons. Although shown in Figure 2 using constant icons, the values for A, B, C, and y_i within the model are the result of submodels formed using many icons.

In a manner similar to that described above, two integrator icons were used to implement Equations (1a) and (1b). Likewise, icons were grouped in a submodel to affect the control strategies shown in Figure 1. These icons represented functions such as proportional and on-off control to operate the fans and heaters according to the control strategy. The room temperature calculated by the integrator associated with Equation (1a) was introduced to the control submodel to determine the operating conditions for the three fans and the heat generated by the heater and lamps. These flow rate and heat generation values were then passed back to the two integrators for calculation of the resulting room and pit air temperatures.

RESULTS AND DISCUSSION

Initially, the model was exercised for various cases to show that it was working properly. To verify the accuracy of the results from the model, several cases were simulated, and numerical solutions were compared with analytical solutions that can be obtained for some reduced forms of the equations. Comparisons of the results between the analytical and numerical solutions showed excellent agreement (Zhang, 2001).

The numerical values for the model parameters are listed in Tables 1 and 2 and are similar to those in the actual system. Table 1 provides the dimensions of the room and pit, overall heat transfer coefficients for the walls and floor between the room and pit, and the pig weight and number. The overall heat transfer coefficient for the walls was obtained from ASHRAE (1995). The overall heat transfer coefficient for the floor was assumed to be the same as that for the wall. Table 2 includes the values of the heat generation terms and the initial values. The power of each lamp is 125 W. The heater has a capacity of 17,400 W. The maximum unobstructed air flow rates were 1.92 m^3/s for both wall fans and 0.81 m^3/s for the pit fan. With the room temperature between 16 and 27°C, the specific sensible heat loss of a pig is approximately 1.7 W/kg (Scott et al., 1983). Choosing the condition that 10 sows (no piglets) occupied the room, and assuming each sow weighed 180 kg, the heat generation for the pigs is $q_p = 3060$ W. The initial values for the room were based on the experimental data, and the initial values for the pit were assumed to be the same as those for the room.

To validate the model, results from the model were compared to real-time data. To obtain the data, the actual room temperature was recorded with a sensor (ACR, 1997) placed in the middle of the room and a similar sensor was placed in the shade outside the building to record the outside air temperature (Achutan et al., 2001). Sensor readings were taken once every 4 minutes over week-long periods over the course of a year. The sensor has a tolerance better than 0.07°C across its range of - 25 to 70°C. An example of the data for the daily variation of the room and outdoor air temperatures is shown in Figure 3 for November 12, 1999. During the early morning times when the outdoor air temperature is low, the room air temperature fluctuates because of the cycling of the heater. As the outdoor air temperature increases during the daylight hours, the fluctuations of the room air temperature diminish and the room air temperature is nearly a constant as a result of the control for the pit fan. The exact operation of the equipment is unavailable so the previous statements about the equipment are assumed scenarios.

To initiate the validation of the model, the data in Figure 3 were used, and several cases were simulated. The data in Figure 3 implied that the set point temperatures before and after 30,000 s are different (estimated as 298 and 296 K). As a first step in the validation process, the simulation time period was chosen from 0 to 30,000 s.

As noted there was no information about the setpoint temperature, hence, the simulation results were acquired for a setpoint temperature of 25°C. Figure 4 shows the data and simulated results for the first 30,000 s using the values of the parameters listed in Tables 1 and 2, and the values of the control parameters previously cited for Figure 1. The simulated room air temperatures and data have somewhat different peak-to-peak ranges. The peak-to-peak range is decided by the dead band for the heater. If the heater dead band is wider, the simulated room air temperature can have the same peak-to-peak range as that for the data. There was no information about the dead band in the actual condition, so the original values given in Figure 1 were used. In addition, the simulated room temperature changes more frequently than the data, and the rates that the room temperature increases and decreases for the simulation are higher than those of the data.

To achieve agreement with the data, several input parameters were modified systematically to establish the effect of each parameter on the simulated results. Case 1 is called the base case and is based on the parameter values cited in Tables 1 and 2 and Figure 1. Parameter values were changed to evaluate the effect of a parameter on the simulated results. It was found that, by decreasing the pit fan maximum air flow rate by about eighty percent, the rates at which the room temperature increase and decrease for the simulation are closer to those of the data. When the air flow rate is decreased, less cold outdoor air enters the room making the room easier to heat and more difficult to cool. Thus, the time for heating decreases, and the time for cooling increases when the air flow rate is decreased. It is reasonable to expect that the maximum air flow capacity for the pit fan was reduced due to pressure losses in the air flow path. Additionally, it was found that, by increasing the room volume by a factor of nine, the simulated room temperatures changed at nearly the same frequency as that for the data. When the room volume is increased, the thermal capacitance of the room, $\rho_a c_a V_r$, increases, so the temperature is more difficult to change. That is a reasonable modification, because the actual room is filled with pigs, pens, and building material, and the thermal capacitance of the room is greater than assuming the room is just filled with air as in Case 1. The increase of the room volume is interpreted as increasing the mass of objects within the room. The modified parameters for Case 2 are given in Table 3.

Figure 5 shows the simulated results and data. The simulated room air temperature matches the data well. The peak-to-peak agreement could be improved by increasing the width of the dead band for the heater. For example, the current dead band produces peak-to-peak temperatures of 1°C, and a dead band of 2°C yields peak-to-peak temperatures of 2°C. Note that only the maximum volumetric air flow rate for the pit fan has been modified.

Due to the qualitative nature of some of the information about the values of the parameters that appear in the model and in view of the intent of the study to develop a model that displays the characteristics of the data so that the effects of different control strategies can be evaluated, a quantitative measure of the agreement between the simulated results and data was not prepared. The intent of the comparisons was not to fine tune the model parameters to achieve agreement but to illustrate that the model does have the ability to predict the data.

The model with the modified parameters for Case 2 was used to simulate the period after 30,000 s for the data in Figure 3. As stated before, there was also no information about the setpoint temperature for this period, hence, the setpoint temperature was selected as 23°C. Figure 6 shows the simulation results along with the data. The variation of the room air temperature at the beginning and ending of the simulation was caused by the on and off cycling of the heater. During the time from 40,000 to 70,000 s, the room air temperature was above the setpoint temperature, and the pit fan speed increased to maintain the setpoint temperature. The agreement between the data and the simulated results is good.

With the simulation results validated for a day, the next challenge was to examine the ability of the simulation results to predict data for multiple days. Data over a 5 day period were used, and the model was given the input parameters for Case 2. Similar to the results shown in Figures 5 and 6, two setpoint temperatures were used each day, namely 25°C for the first 12 hours and 21°C for the second 12 hours. Figure 7 displays the simulated results. The relative changes in simulated room air temperatures and the data are in agreement although there is more cycling of the heater as predicted by the simulation than indicated by the data.

Next, three kinds of whole-day data were selected to represent typical cold, mild, and hot weather conditions. Case 2 input parameters were used for the simulated results. The setpoint temperatures and equipment operation for the actual conditions are listed in Table 4.

For the cold day, during the simulation, the two wall fans and the lamps are off, the pit fan works at its minimum speed, and the heater cycles on and off based on the difference between the room air temperature and the setpoint temperature. Figure 8 provides the actual and simulated room air temperatures for a cold day. The simulated temperatures change at nearly the same frequency as that of the data. The peak-to-peak range of the simulated results is narrower than that of the data. This difference is because the dead band of the heater in the actual condition may be wider than that for the simulated conditions.

For the hot day, the heater and lamps are off, the pit fan works at its maximum speed, and the two wall fans operate based on the difference between the room temperature and the setpoint temperature. Figure 9 shows the data and simulated room temperatures for the hot day. At the beginning of the day, the outdoor air temperature is not very high, and the variable speed wall fan changes speed and the on-off wall fan does not work for the simulation. The simulated room air temperature varies within a narrow range, because the variable speed wall fan has a dead band in the simulation. Without this dead band, the simulation does not work properly. However, in the actual condition, the variable speed wall fan does not have a dead band. With an increase of the outdoor air temperature, the variable speed wall fan reaches its maximum speed, and the on-off wall fan begins to operate. The simulated room air temperature follows the data closely, and both are nearly equal to the outdoor air temperature.

For the mild day, shown in Figure 10, the simulated room air temperature were higher than the original data. To achieve agreement, it was necessary to set the heat generation rate for the pigs to zero, thereby implying there were no pigs in the building for the day. As displayed in Figure 11, the simulated results for no pigs agree with the data. For the simulation in Figure 11, the wall fans and lamps are off, the pit fan works at its minimum speed, and the heater cycles on and off based on the difference between the room air temperature and the setpoint temperature.

SUMMARY AND CONCLUSIONS

A model was developed to evaluate the IAQ of a swine ventilation system that is comprised of three fans. The model was used to study the ability of the model to predict actual data for a modern swine building. The model consists of two equations describing the dynamic behavior of the room and pit air temperatures and a controller. Application of actual values of the parameters allows the model to calculate and display the air temperature in the room and pit. The numerical solutions from the model were produced using an icon-based software package. The numerical model was validated by comparing the numerical results with experimental results. Data for a 5-day period and three kinds of whole-day, namely, cold, mild, and hot weather conditions were used for this validation process. To achieve agreement between the model and experimental data, some of the input parameters were modified in a systematic manner to evaluate the impact of each parameter on the model results. The final modifications consisted of increasing the mass of objects in the room and decreasing the maximum airflow rate of the pit fan. These modifications demonstrated that the application of the original specific known parameter values did not result in agreement with the experimental data but indicate that the model is sufficiently complex to allow for reasonable adjustments necessary to reach agreement. The predicted room air temperatures with the modified parameters match closely the data for the three typical cold, mild and hot days and the consecutive five days.

REFERENCES

Achutan, C., Z. E. Nelson, A. W. Karsten, and P. T. O'Shaughnessy, 2001. Temporal variation in swine confinement indoor air quality," *Livestock Environment VI, Proceedings of the 6th International Symposium, Louisville, Kentucky:* 579-586. May 21-23.

ACR, Smart Reader Plus Reference guide, ACR Systems Inc., Surrey, British Columbia, 1997.

Axaopoulos, P., P. Panagakis, and S. Kyritsis, "Computer simulation assessment of the thermal microenvironment of growing pigs under summer conditions," *Trans. ASAE.* 35(3): pp. 1005-1009,1992

Axaopoulos, P., P. Panagakis, G. Pitsilis, and S. Kyritsis, "AGRISIM: A PC user-friendly trasient simulation program fro growing-finishing swine buildings," *Trans. ASAE.* 10(5): pp. 735-738, 1994.

ASHRAE, ASHRAE Handbook: 1995 Fundamentals, American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc. Atlanta, GA, 1995.

Donham, K. J., P. Haglind, Y. Peterson, R. Rylander, and L. Belin, "Environmental and health studies of workers in Swedish confinement buildings," *British Journal of Industrial Medicine.* 40: pp. 31-37, 1989.

Murphy, J. P., D. D. Jones, and L. L. Christianson, "Mechanical ventilation of swine buildings," *Pork Industry Handbook:* pp. 1-8, Iowa State University Extension, 1991.

Nicas, M 1996. "Estimating exposure intensity in an imperfectly mixed room," *AIHA Journal* (57): pp. 542-550, 1996.

Panagakis, P, P. Axaopoulos, and S. Kyritsis, "Misting control strategy for growing-swine under summer conditions," *Trans. ASAE.* 12(6): pp. 747-751, 1996.

Simulink, Version 3.0, The MathWorks, Inc. Natick, Massachusetts, 1998.

Togari, S., Y. Arai, and K. Miura, "A simplified model for predicting vertical temperature distribution in a large space," *Trans. ASHRAE: Research* : pp. 84-99, 1993.

Varifan, ECS 5M, Environment control system, 1996.

Zhang, L., T. F. Smith, and P. T. O'Shaughnessy, "Development of a simulation model for a ventilation system for swine confinement," *Livestock environment VI, proceedings of the 6th international symposium, , Louisville, Kentucky:* pp 293-300, May 21-23, 2001

Zhang, Y. and E. M. Barber, "Variable ventilation rate control below the heat-deficit temperature in cold-climate livestock buildings," *Trans. ASAE.* 36(5): pp. 1473-1482, 1993.

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NOMENCLATURE

A_{pr} Area of the floor (m^2)

A_{pw} Side wall area of pit (m^2)

A_{rw} Side wall area of room (m^2)

c_a Specific heat of air (J/kg-K)

C_{ex} Air exchange coefficient

q_{gen} Total heat generation in the room (W)

q_h Heat generation by heater (W)

q_l Heat generation by lumps (W)

q_p Heat generation by pigs (W)

Q_t Total air flow rate (m^3/s)

Q_1 Flow rate of first wall fan (m^3/s)

Q_2 Flow rate of second wall fan(m^3/s)

Q_p Flow rate of pit fan (m^3/s)

t Time (s)

T_p Pit air temperature (K)

T_r Room air temperature (K)

T_o Outdoor air temperature (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)

U_{rw} Overall heat transfer coefficient of side walls of room (W/m^2-K)

V_p Pit volume (m^3)

V_r Room volume (m^3)

ρ_a Density of air (kg/m^3)

Table 1 Buildings and animal parameters used for the simulation.

Dimensions (m)	Room	Pit
Width	7	7
Length	9	9
Height	2.4	0.9
Overall heat transfer coefficient (W/m^2-K)		
Room walls	3.3	
Room floor	3.3	
Pit walls	3.3	
Animal parameters		
Pig weight (kg)	180	
Number of pigs	10	

Table 2 Numerical values of general model parameters.

Parameter	Value	Unit
Air density	1.225	kg/m^3
Air specific heat	1005.4	J/kg-K
Heat generation per pig	306	W
Heat generation per lamp	125	W
Number of lamps	10	N/A
Heat generation of heater	17400	W
Max. flow rate of on-off wall fan	1.92	m^3/s
Max. flow rate of variable speed wall fan	1.92	m^3/s
Max. flow rate of pit fan	0.81	m^3/s
Initial room and pit temperature	295	K

Table 3 Validation cases.

Case	Adjusted variable	Q_{pmax}(m^3/s)	V_r (m^3)
1	Base	0.81	151.2
2	Combination	0.15	1400

Table 4 Settings for three typical weather days.

	cold	mild	hot
Setpoint temperature (F)	74	73	72
Pit fan minimum speed (%)	60	56	64
Wall fan 1 minimum speed (%)	54	54	56

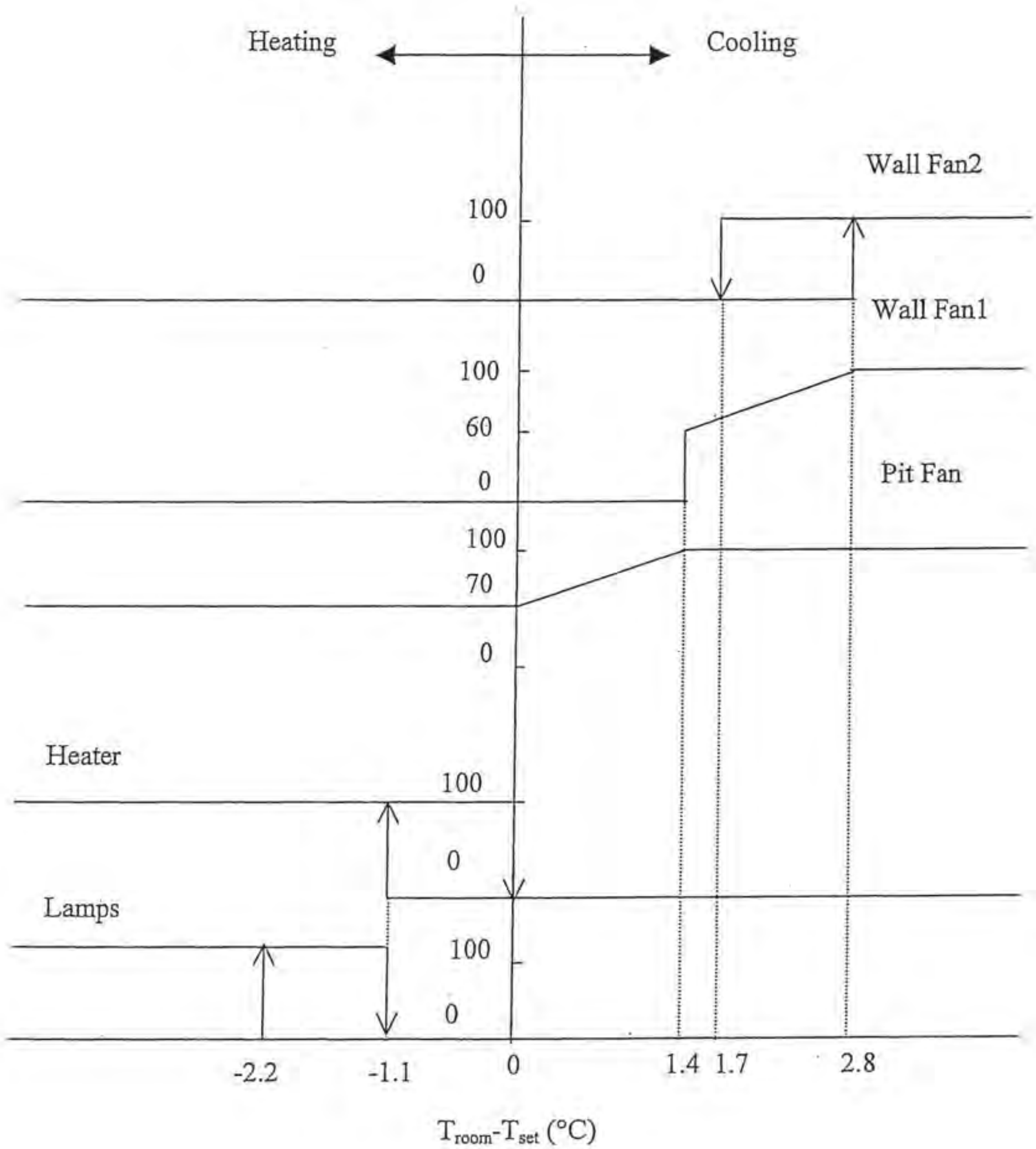

Figure 1. Control strategies.

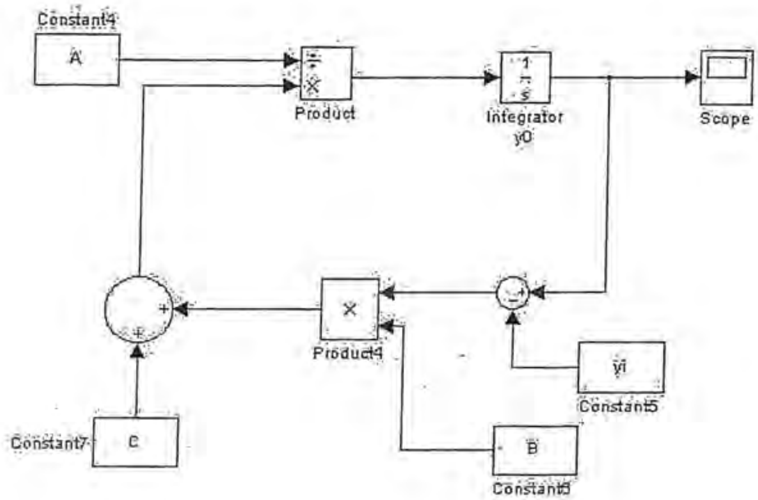

Figure 2 Schematic diagram of icons for Simulink.

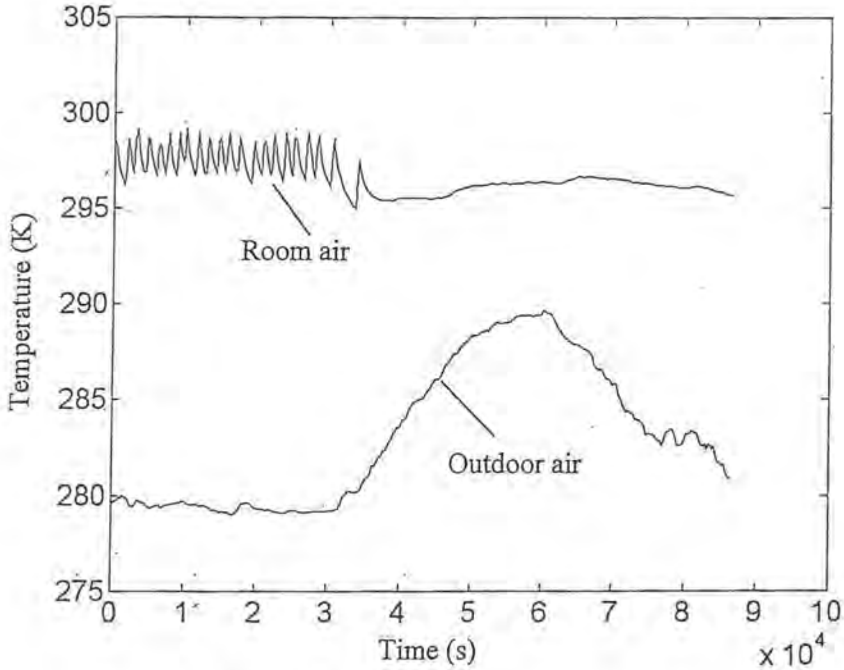

Figure 3 Temperature data.

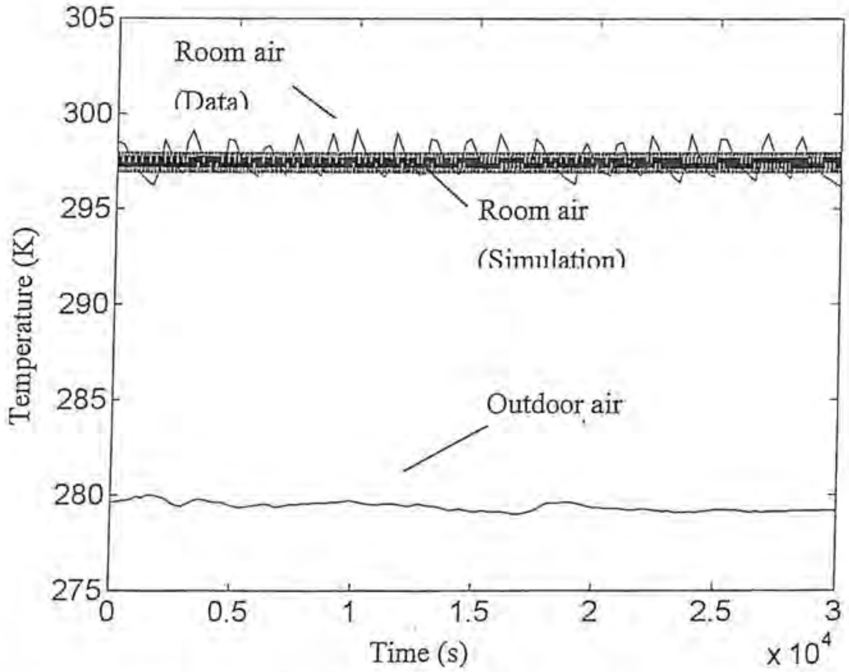

Figure 4 Data and simulated temperature for Case 1.

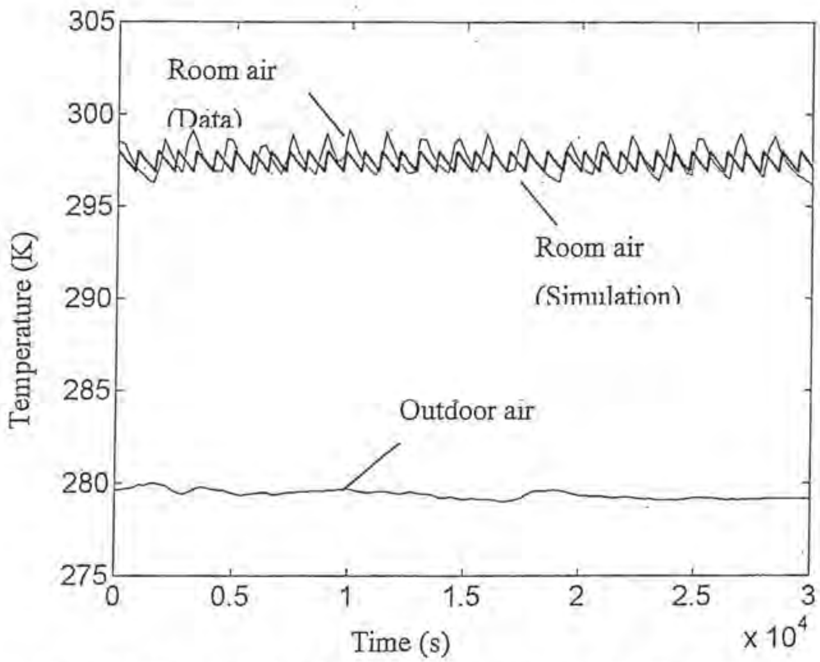

Figure 5 Data and simulated room temperatures for Case 2.

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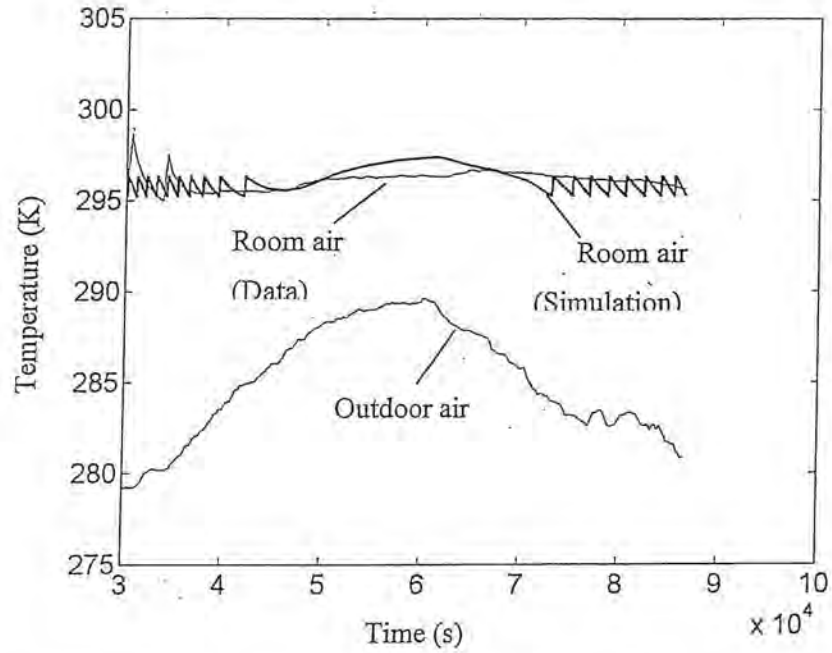

Figure 6 Data and simulated room temperatures after 30,000 s.

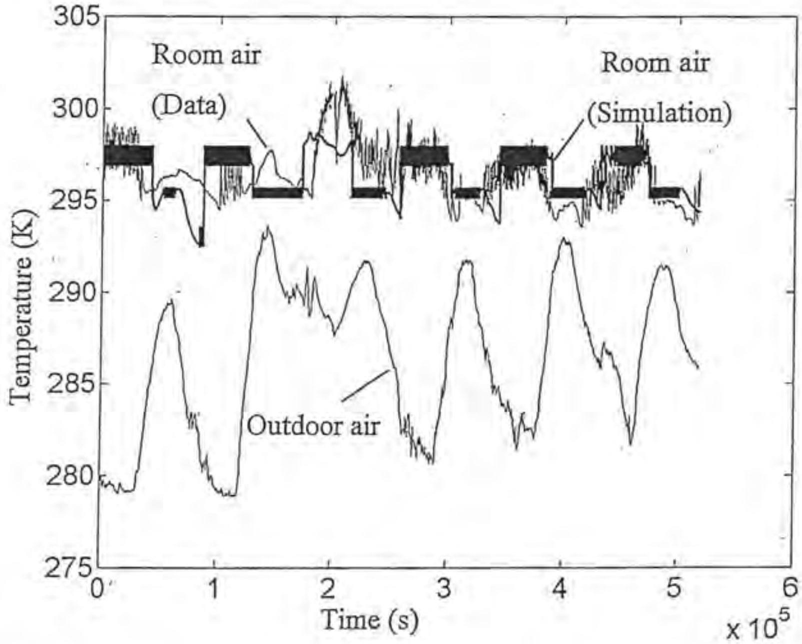

Figure 7 Data and simulated room temperatures for several days.

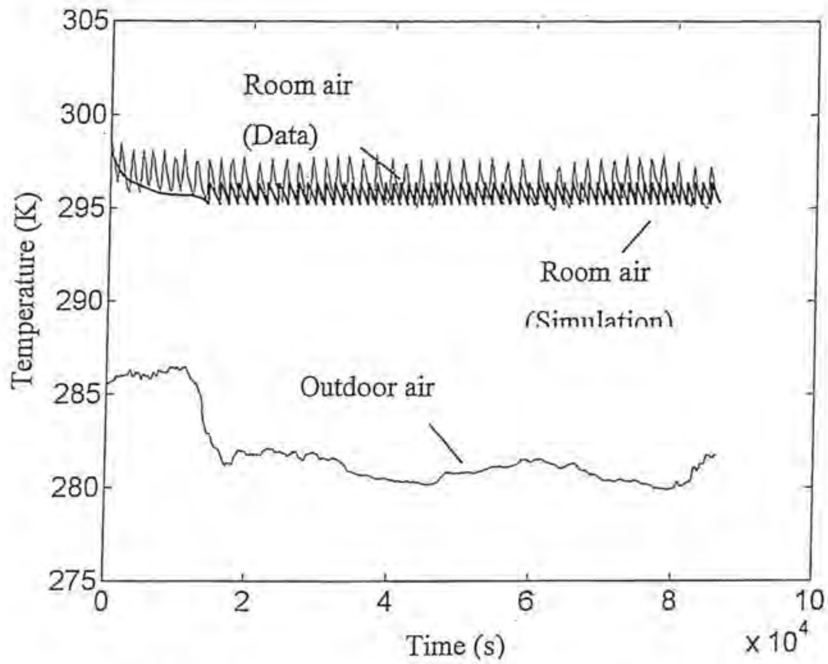

Figure 8 Data and simulated temperatures for cold day.

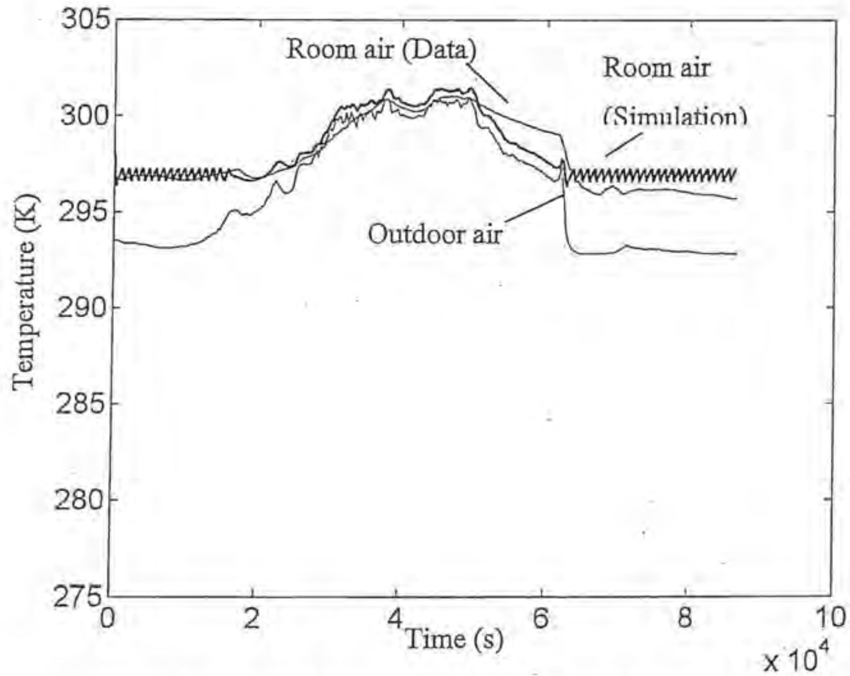

Figure 9 Data and simulated temperatures for hot day.

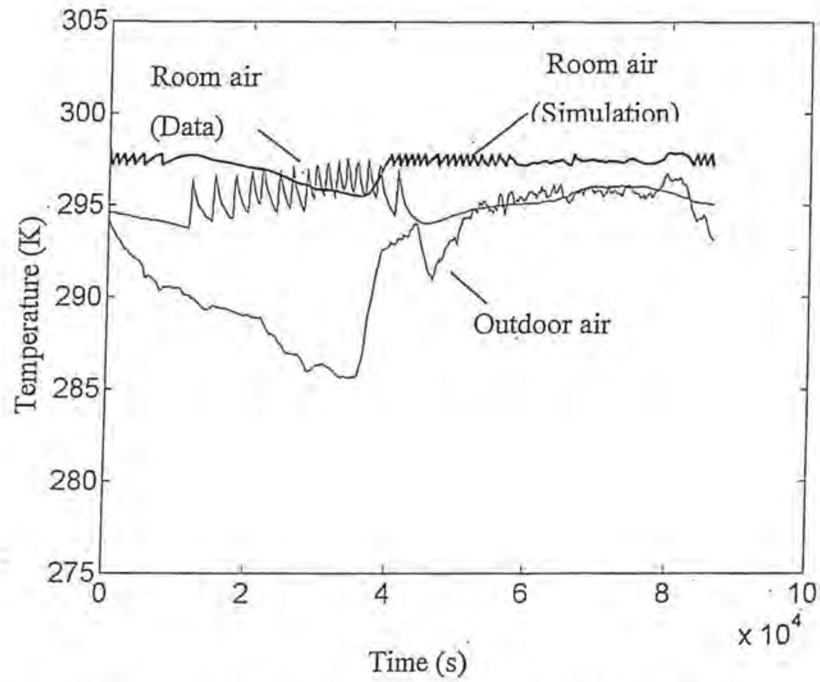

Figure 10 Data and simulated temperatures for mild day with pigs.

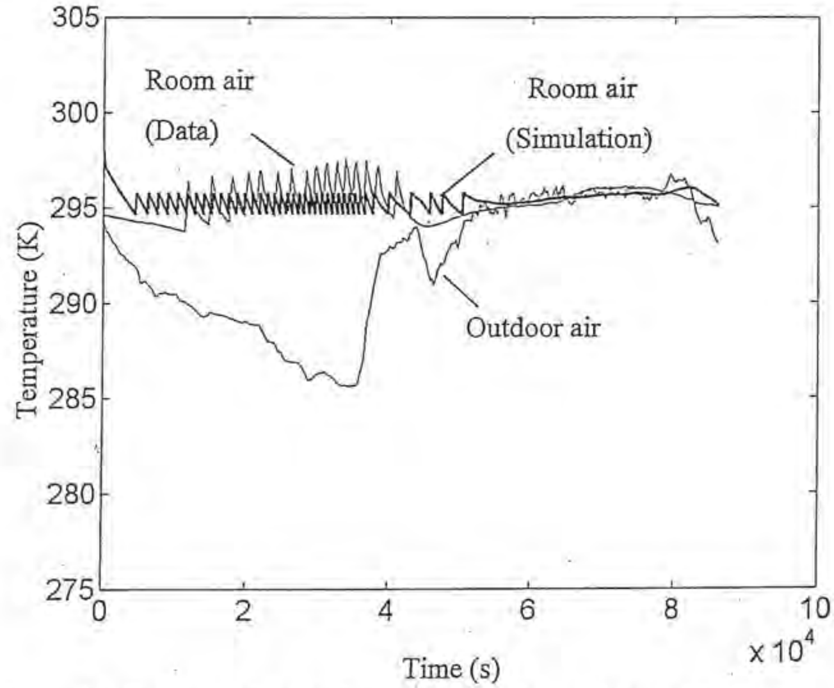

Figure 11 Data and simulated temperatures for mild day without pigs.