CLIMATE CONTROL OF NATURAL VENTILATED PIG HOUSES

J. Bontsema, G. van Straten, L. Salomons
Wageningen Agricultural University
Dept. of Agricultural Engineering and Physics
Bomenweg 4
NL-6703 HD Wageningen
The Netherlands

C.E. Van 't Klooster
DLO-Institute for Agricultural and
Environm.Engineering Dept. of Livestock
Engineering
P.O. Box 43
NL-6700 AA Wageningen
The Netherlands

Abstract

Ventilation in pig houses is important for maintaining a good climate for the welfare of animals and humans and for an optimal production. Mechanical ventilation has a good performance, since the ventilation rate can easily be controlled, but it is energy demanding, whereas natural ventilation is cheap but due to large variations in the outdoor conditions it can cause unwanted variations in the ventilation rate. To improve the performance of natural ventilation a good control scheme is necessary. Since in this case controller tuning is difficult in the practical situation, due to all influences on the climate, a dynamic model is discussed, so that the tuning can be done off-line, which means that the tuning of the controllers is done in simulations. The model of the indoor climate is validated by measurements of the temperature of the pig house. The performance of the control scheme, in which standard PID controllers are used in a cascade configuration, is shown by simulations.

1. Introduction

For the welfare of the animals and humans in pig houses ventilation is necessary. Ventilation can be done by fans or by using varying ventilation openings in the walls and in the top of the roof of the pig house. The latter method of ventilation is called natural ventilation since it is determined by the outside wind and temperature. From the viewpoint of energy use natural ventilation is to be preferred since is uses much less energy than mechanical ventilation. For natural ventilation, only a small amount of electricity is needed for some servo-motors to vary the ventilation openings. A 90% reduction in use of electric energy can be realized if mechanical ventilation in pighouses is replaced by natural ventilation (Van 't Klooster, 1994).

Since the outside conditions can vary rapidly, a good control scheme is necessary to maintain a good internal climate. Since in pig houses heating is also used, especially for young animals, the control should also be designed in such a way that the heating is used efficiently.

In this paper, first a model is discussed for the pig house climate, including the influence of the animals. This model is then validated using measured data of the climate and outside conditions. The performance of the model is discussed. The model will be used for testing the control scheme. To validate the model, measurements of the temperature in the pig house were used.

The control scheme consists of two cascade controllers (master/slave controllers), one for the inside temperature and one for the inside carbon dioxide concentration. The underlying master and slave controllers are of PID-type, whereas the slave controller for the heating is an on-off controller.

A model which calculates the ventilation rate from outside wind speed and direction, is

Proc. Math. and Contr. Applic.
in Agric. and Hortic.
Ed. W. Day, P.C. Young
Acta Hort. 406. ISHS 1996

used to correct the ventilation openings in such a way that rapidly changing outdoor conditions will only have a minor influence on the inside climate. This part is the slave controller in the cascade loop. The control scheme is tested using simulations with the pig house climate model. The temperature can be controlled with a maximum deviation from the desired temperature of 0.3 °C and the carbon dioxide concentration does not exceed the maximum allowable value with more than 1.5%.

2. Models

From the standard energy balance and the mass balance for the water vapour and under the assumption of a homogeneous and constant volume, the following differential equation for the indoor temperature can be derived (for details see Van 't Klooster, 1994 and Salomons, 1994):

$$\begin{aligned}\frac{dT_i}{dt} = {} & \left(\frac{-\rho_o*c_l+\rho_o*c_d*X_o}{(c_l+c_d*X_i)*\rho_i}*\frac{V_f}{V}-\frac{c_d*Q_l*N}{(c_l+c_d*X_i)*\rho_i*\epsilon_i}\right)*T_i+\\ & \left(\frac{\rho_o*c_l*T_o+\rho_o*(\epsilon_o-\epsilon_i)*X_o+\rho_o*c_{do}*T_o*X_o}{(c_l+c_d*X_i)*\rho_i*\epsilon_i}\right)*\frac{V_f}{V}+\\ & \frac{Q_s*N+Q_h-Q_b+Q_r}{(c_l+c_d*X_i)*\rho_i*V}\end{aligned} \qquad (1)$$

Here T_i and T_o are the inside and outside temperature (°C), t is the time (s), X_i and X_o are the indoor and outdoor water vapour content of air (kg H_2O/kg dry air), ρ_i and ρ_o are the density of the indoor and outdoor air, V is the volume of the room (m^3), V_f is the ventilation rate (m^3/s) through the building, Q_s and Q_l are the sensible and latent heat production of the pigs, N is the number of pigs, ε_i and ε_o denote the evaporation heat of water (J/kg), indoor and outdoor, c_d , c_{do} and c_l are the specific heat of water vapour, water vapour outdoor and dry air respectively, Q_r is the heat influence from outside radiation, Q_h is the heat supplied by the heater, Q_b denotes the heat losses through the walls and floor. To model the heat losses through the walls and the floor and the heat storage in the walls and the floor, the indoor walls, outdoor walls and the floor are divided in five layers and for each layer a differential equation is derived (for precise details see Salomons, 1994), which introduces an extra of 15 state variables. The sensible and latent heat production Q_s and Q_l can be related to feed intake, energy conversion of the feed and age of the animals (Van 't Klooster, 1994 and Salomons, 1994).

The time evolution of carbon dioxide is given by the following equation:

$$\frac{dg_i}{dt}=\frac{\rho_o}{\rho_i*V}*V_f*g_o-\frac{V_f}{V}*g_i+\frac{G_a}{\rho_i*V} \qquad (2)$$

Here g_i and g_o are the indoor and outdoor CO_2-concentration (kg/kg air), G_a is the CO_2-production of the animals. It is assumed that there is no CO_2-absorbtion of the room and since electric heating is used there is no CO_2-production from heating. G_a can be related to feed intake, energy conversion of the feed and age of the animals (Van 't Klooster, 1994 and Salomons, 1994).

Heating is supplied by an electric heater with a power of 9 kW and the heat is distributed by a built-in blower with an air flow capacity of 1160 m^2/h. The heater is modelled as a series connection of two first order systems. So the transfer from the power (P) to the emitted heat (Q_h) is with Laplace transforms given by (Palm, 1986):

$$G(s) = \frac{Q_h(s)}{P(s)} = \frac{1}{(\tau_{h1}+1)\,(\tau_{h2}+1)} \tag{3}$$

From calibration it followed that τ_{h1} = 50 s and τ_{h2} = 420 s. It turned out that is important to model the dynamics of the heater. Taking $G(s) = 1$, i.e. instantaneous heat supply, gave a great discrepancy between measured and simulated temperature and it turned out that modelling the heater as a second order systems (eqn. 3) gave a good agreement between measured and simulated temperatures. Also as in Zhang et all, 1992, a first order transfer for the heater has been considered, but in our case the second order transfer has to be preferred.

The ventilation can be calculated from wind speed, wind direction, indoor and outdoor temperature and aperture of the vents (for details see Salomons, 1994 and Kornaat and Knoll, 1992).

3. Control scheme

In controlling the indoor climate two types of controllers are used. In the heating process an on/off controller is used and for the other controllers PID controllers have been used.

If $e(t)$ is the error between the set point and the controlled variable and $f(t)$ is the output of the controller and so the input for the process then for a PID controller the relation between $e(t)$ and $f(t)$ is given by (Palm, 1986):

$$f(t) = K_p\left(1 + \frac{1}{\tau_I}\int_0^t e(t)\,dt + \tau_D \frac{de(t)}{dt}\right) \tag{4}$$

Here K_P is the proportional gain, τ_I is the integral time constant and τ_D is the derivative time constant. For practical implementation the PD-part is replaced by a so-called tame PD part. This means that the output of the controller is filtered by a first order system with a time constant of $0.2\tau_D$, in this way it is avoided that high frequency noise is strongly amplified by the derivative part (Palm, 1986). Since there are constraints on the inputs to the process such as a maximum available heating power and a maximum opening of the vents, the integral part of the controller can give rise to so-called integral wind-up (Palm, 1986). In simulations and in practical implementation an anti wind-up mechanism has to be used. In simulation an anti wind-up algorithm from Morari, 1993 has been used, whereas in practice to prevent wind-up a velocity form of a digital PID can be used (Palm, 1986).

Furthermore a so-called cascade (or master-slave) configuration (Palm, 1986) has been used. The general form of this configuration is given in figure 1.

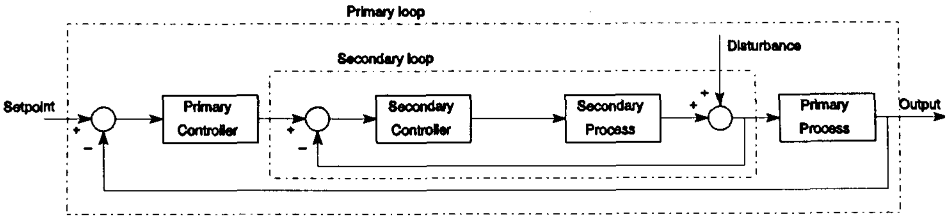

Figure 1. Cascade control configuration.

Cascade control can be used if the process can be divided in two parts, the primary process and the secondary process and if a disturbance, which can be measured, is acting on the input of the primary process. Furthermore it is assumed that the secondary process is much faster than the primary process. In the process considered in this paper in the CO_2-loop the primary process is the climate in the pig house and the secondary process is the ventilation system. The disturbance is then the outdoor wind speed and direction. The output of the secondary process together with the disturbance is compared with the output of the primary controller and fed back via the secondary controller. In this way the influence of the disturbance can be corrected very fast. Notice that the set point of the secondary loop is determined by the output of the primary controller (the master). The secondary loop does not affect the stability of the overall loop, and therefore high gains can be used in the secondary loop.

The proposed control configuration for the complete climate control in the pig house is given in fig. 2.

The heating can only be switched on and off. The on/off controller causes some rapidly varying disturbances in the temperature, therefore also for the heating part of the temperature control a cascade configuration has been used. The measured indoor temperature is compared with both the minimum and maximum allowed temperature. If the indoor temperature is below the minimum temperature, the difference is fed through the controller block PID_1 which then calculates the demanded heat supply, this quantity is then compared with the heat supplied by the heater and depending on the sign of the difference the heater is put on or off. The on/off controller uses a bandwidth in order to avoid to rapid switches. The heat supplied by the heater is calculated from eqn. 3, since it was not measured.

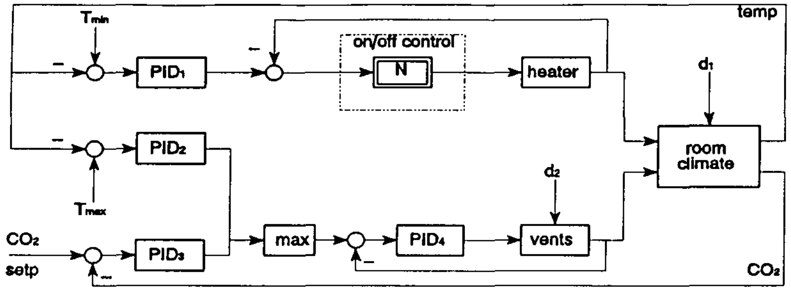

Figure 2. Climate control scheme for natural ventilated pig houses.

If the temperature exceeds the maximum temperature, PID_1 is not used and the temperature difference will be processed by the controller block PID_2, which determines a ventilation rate. This value is compared with the result from block PID_3 and the maximum value is send to the secondary controller PID_4. Note that both PID_2 with PID_4 and PID_3 with PID_4 form a cascade control loop. The ventilation rate due to the vents will be influenced seriously by the outdoor wind speed and wind direction (the signal d_2 in figure 2). Since the ventilation rate is not measured, a model is used to estimate this (Salomons, 1994). The calculated ventilation is then compared with the desired ventilation rate from the maximum block and this difference is send to the block PID_4, which in its turn calculates the necessary aperture of the ventilation opening.

4. Results

In figure 3 the results of an experiment are shown in which the pig house without animals is heated at night during a period of 21/2 hours. As can be seen the outdoor temperature is almost constant. The indoor temperature does not reach a steady state in the heating phase. The simulated temperature clearly indicates the dynamics of the measured temperature and the error between simulated and measured temperature is less then 2°. The measured temperature is the average of the measured temperature on animal level and the measured temperature on a height of 1.50 m. It turned out that between these two temperatures there is in general a difference of 3 °C (Van 't Klooster, 1994). The assumption that a pig house is a perfectly mixed room is to restrictive and should be removed in future.

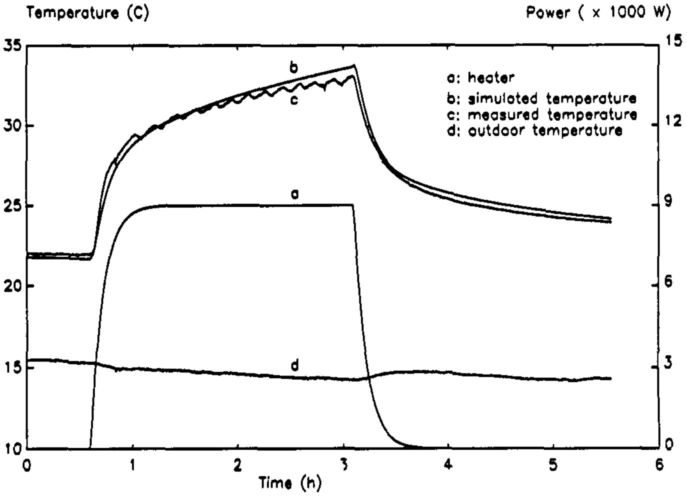

Figure 3. Measured and simulated temperature in a pig house without animals.
(a) supplied heat, P (W)
(b) simulated indoor temperature, T_i (°C)
(c) measured indoor temperature, T_i (°C)
(d) outdoor temperature, T_o (°C).

The requirement for temperature control in pighouses is that the temperature should stay between certain limits, which is called the comfort zone. The limits depend on the age of the animals. In order to see the effect of the control configuration a simulation was performed in which the level of the comfort zone is changed in time. The number of pigs is 70 and their age 50 days. The outdoor conditions are shown in figure 4.

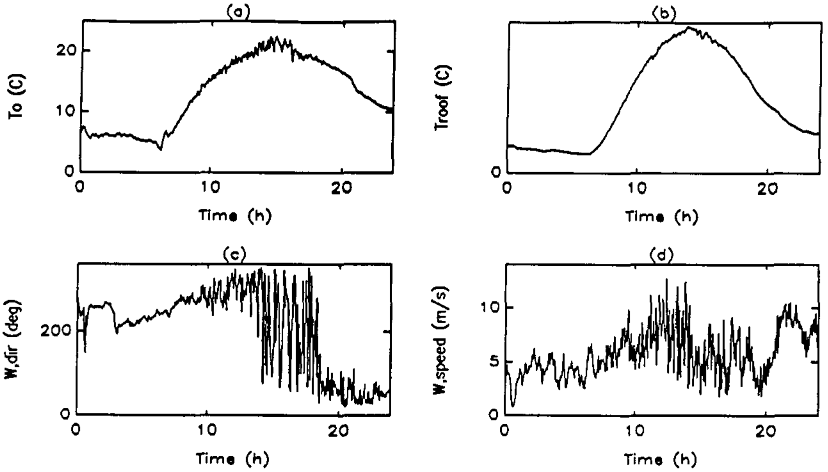

Figure 4. The outdoor conditions used in the simulation.
(a) T_O: the outdoor temperature (°C)
(b) T_{roof}: the temperature of the roof (°C)
(c) W_{dir}: winddirection (°)
(d) W_{speed}: windspeed (m/s).

The bandwidth of the comfortzone zone is the difference between the upper and lower temperature setpoints and was chosen to be 2 °C, see figure 5. The control system should force the temperature to stay in the comfortzone. From fig. 5a it can be seen that in steady state the requirements are met. It can also be concluded that it takes a lot of time to heat the pig house to a high desired temperature and also cooling by ventilating can take a few hours if the desired temperature level is decreased considerably. Once the temperature is near the desired zone, it turns out that in case heating is necessary the temperature stays within 0.1 °C of the lower setpoint, i.e. heating is minimal. In case cooling is necessary, the temperature stays within 0.1 °C of the upper setpoint. The maximum level of carbon dioxide was chosen to be 0.0037 kg/kg air (= 2000 ppm). From figure 5c and 5d it is clear that the control system performs very well, the maximum level is only exceeded with a maximum of 0.00005 kg/kg air (< 1.5%).

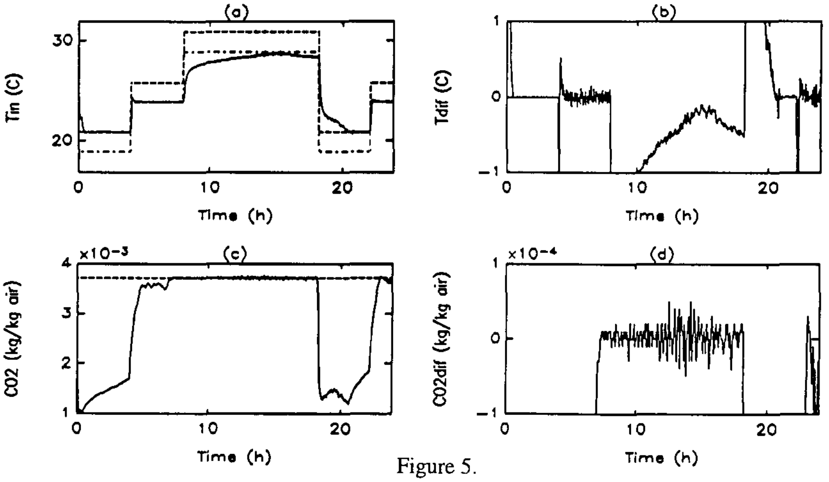

Figure 5.

Figure 5. Indoor temperature and indoor CO_2 concentration.
(a) __: T_i, the indoor temperature (°C)
--: upper temperature setpoint
-.: lower temperature setpoint
(b) T_{dif} : difference between setpoint and actual indoor temperature (°C)
(c) __: CO_2, indoor carbon dioxide concentration (kg/kg air)
--: carbon dioxide setpoint
(d) $CO_{2.dif}$: difference between setpoint and actual indoor carbon dioxide concentration (kg/kg air).

In figure 6 the control inputs are shown. In the first four hours of the desired temperature traject the room has to be cooled as can be seen from figure 6a (no heating power) and 6b (vents maximally open). Note that the calculated aperture of the vents exceeds the upper constraint of 100% (figure 6c). Due to the large amount of ventilation the CO_2 concentration is far below the maximum allowable value. In the second part of the desired temperature traject, from 5 to 8 h., the upper and lower temperature setpoints are raised by 5°C. Heating is put on and the vents are closed until the maximum CO_2 concentration is reached (figures 5c and 6b). Note the rapidly varying nature of the heating power (figure 6a), causing rapid (but small) variations in the indoor temperature (figures 5a and 5b). The control however works perfectly well, the indoor temperature rapidly reaches the lower setpoint and the CO_2 concentration stays very close to the maximum value. In the third part, from 8 to 18 h. the temperature setpoints are again raised by 5°C. The heating is put on its maximum (figure 6a) and the vents are partly opened to maintain the CO_2 concentration on its maximum (figure 5c). From figure 6d it can be seen that the ventilation rate is quite smooth, whereas the variations in the aperture of the vents are large. This is the effect of the cascade control, the variations in the outdoor windspeed and direction are directly suppressed by the slave controller for the ventilation system. In the fourth part, from 18 to 22 h., the level of the comfort zone is decreased with 10 °C. The aperture of the vents is set to 100% and heating is put off. Since the aperture of the vents is on its maximum, the cascade control will have no effect, which directly can be seen from figure 6d, there are now large variations in the ventilation rate. From figures 5a and 5b it can be seen that the anti wind up mechanism in the integral part of the controllers works satisfactorily, there is hardly any overshoot.

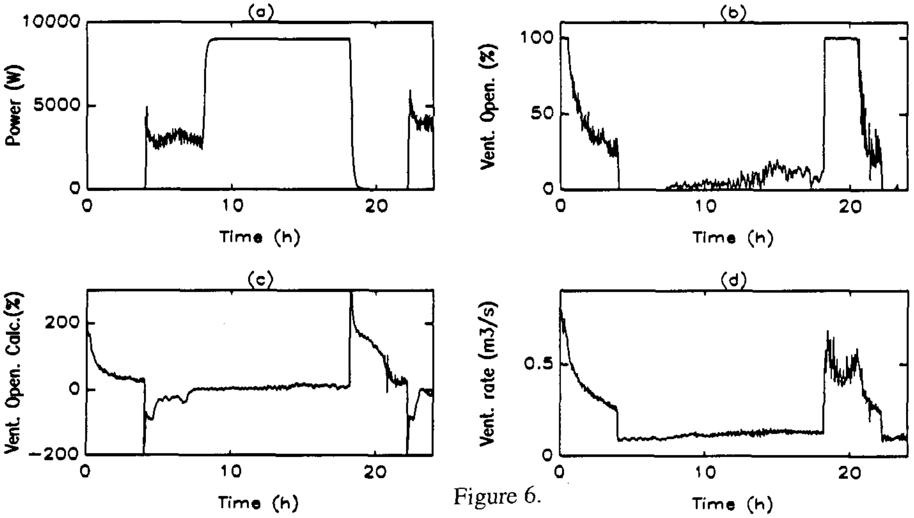

Figure 6.

Figure 6. The control inputs: heating power and aperture of the vents.
(a) P: heating power (W)
(b) Actual aperture of the ventilation opening (%)
(c) Calculated aperture of the ventilation opening (%)
(d) V_f: Ventilation rate (m_3/s).

5. Conclusions

In this paper a dynamic model of the climate in natural ventilated pig houses, which only depend on physical parameters of the building, feed etc. has been described. The model simulated the measured temperature good and another advantage is that depends on easy to be measured weather data. Such a model is a premise for controller manufacturers, since they can use it for design of control schemes and for off-line tuning of the controllers, so cumbersome testing in practical circumstances and on-line tuning can be avoided.

The proposed control figuration with two cascade loops meets the specification, the maximum allowable CO_2 is hardly exceeded, not more than 1.5% and the temperature is forced to the lower setpoint of the comfort zone if heating is required and otherwise it is maintained on the upper setpoint, so saving energy. The deviations from the desired temperature in steady state are not more than 0.3 °C.

In extreme situations, i.e. large temperature steps, heating and cooling by ventilation is not always sufficient, due to which it takes longer before the desired situation is reached.

The control scheme can easily be implemented in hard and/or software. The required measurements are room temperature, CO_2 concentration and outdoor weather conditions.

References

Kornaat, W., and Knoll, B., 1992. Ventilation research in pig houses (in Dutch). TNO report B-92-0406, TNO, The Hague.

Morari, M., 1993. Some control problems in the process industries. In Trentelman, H.L., Willems, J.C. (eds.). Essays on control: perspectives in the theory and its applications. Birkhäuser, Boston.

Palm, J.W., 1986. Control systems engineering. Wiley, New York.

Salomons, L., 1994. Modelling and control of the climate in natural ventilated pig houses (in Dutch). MSc. Thesis, University of Wageningen.

Van 't Klooster, C.E., 1994. Implementation of natural ventilation in pig houses. Ph.D. Thesis, University of Wageningen.

Zhang, Y., Barber, E.M., and Sokhansanj, S., 1992. A model of the dynamic thermal environment in livestock buildings. J. agric. Engng Res. 53: 103-122.