# ANALYSIS OF LIVESTOCK ENVIRONMENT CONTROL BY SIMULATION TECHNIQUE AND FIELD DATA.

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## Abstract

A dynamic model based on physical laws and field measurements has been developed to simulate temperature, humidity and gas concentration in livestock buildings and the emission of ammonia from these buildings. The model consists of several sub models and permits to evaluate different control algorithms for heating and ventilation of livestock buildings. For each control algorithm the dynamic evolution of the resulting inside temperature and humidity are calculated together with the corresponding energy use for the specified heating and ventilation system.

By using this simulation technique a new climate control algorithm for livestock buildings has been designed, which, compared to a traditional climate control algorithm, has several advantages in terms of energy use, reduced temperature fluctuations and reduced ammonia emission.

In a validation experiment is was found that the agreement between the simulated and measured temperature was less than 0.4°C, although the difference between the temperature measured at different locations within the building is higher than the difference between the simulated and the measured temperature.

It was concluded that simulation technique offers a powerful tool to develop new control strategies, but that more knowledge is needed about the process of three dimensional energy and mass transportation around a living organism.

## 1. Problem

In modern livestock buildings, the production results (growth rate, food efficiency, mortality, etc..) are strongly influenced by the environmental conditions during the growing period (Verstegen et al., 1984; Geers et al., 1984).
In a ventilated livestock building the resulting inside climate (temperature, humidity, gas concentration, air velocity, etc.) is mainly determined by the used process inputs: ventilation rate, heat supply and air flow pattern. The influence of ventilation rate on the resulting inside climate and the energy use has been described in literature and is known since a long time ( King, 1908; Reece and Harwood, 1974; Buffington and Skinner, 1976; Surbrook et al., 1979; Cole, 1980; Clark, 1981; Berckmans and Goedseels, 1986).
Although the influence of the control inputs on the resulting inside climate has been studied several times, little progress has been made in the development of control algorithms for livestock houses. A whole range of new technology (digital controllers, sensors, microchip, etc.) is available to develop new control algorithms, but to obtain more benefit from this new technology more knowledge is required about the interaction between the process and the controller. It seems logic that by new technology becoming more reliable and cheaper, new control equipment will be applied.

An appropriate technique to develop and to analyse the efficiency of control algorithms is simulation technique. The last decades, different authors described mathematical models to simulate the inside climate in a livestock building. Several techniques have been used to build a mathematical model such as: harmonic analysis (Jordan et al., 1965; Christianson and Hellickson, 1977; Albright and Scott, 1974); Z-transfer function method (Buffington, 1975; Mitalas and Arsenault, 1970); the thermal response method with Laplace transformation (Buffington, 1981). However, due to different limitations (constant ventilation rate, linear relation between ventilation rate and inside temperature, assumption of constant inside temperature over a longer time period, etc.) none of those models is really suited to evaluate control algorithms.

From more recent literature (Chao et al., 1992; Parmar et al., 1992; Zhang et al., 1992; Gates et al., 1991; Axaopoulos et al., 1992) it can be seen that one of the most widely used approaches is to make the basic assumption of a perfectly mixed airspace in the whole livestock building and to simulate the inside temperature, gas and moisture concentration with the steady state or dynamic energy and mass equations.

Most of the authors never did a lot of validation work. Consequently the open question remains about how reliable such a simulation model is. Especially when these equations are used in combination with other sub models of the total system as used in simulations to evaluate control algorithms.

## 2. Objective

It is the objective of this paper to illustrate the capability of a dynamic simulation model to develop and to evaluate climate control algorithms for livestock buildings.

This simulation technique is used on a yearly base to develop an adapted control algorithm for livestock buildings, that, compared to a traditional temperature proportional controller, is able to:

- reduce the daily temperature fluctuations in the animal house
- reduce the risk for cold draughts on the animals
- reduce the ammonia emission from livestock buildings
- minimise the energy consumption for heating and ventilation

To validate the simulation model, the simulated results are compared with field measurements.

## 3. Method

### 3.1. Simulation model

Figure 1 shows the different parts of the global simulation model (Adapted from Berckmans, 1986). The different sub-systems of a heated and mechanical ventilated livestock building are modelled with different sub models: the process, the heating system, the fan, the temperature sensor, the controller and the ammonia emission.

Within the sub model of the process the assumption of a perfectly mixed air space for the whole livestock building is accepted and a dynamic heat and mass balance is used. Below, a short description of the model parts is given, while we refer to previous literature for a more detailed description (Berckmans 1986; Berckmans et al, 1992).

Each sub model will be discussed separately and the way in which the program uses the output of the models will be explained briefly.

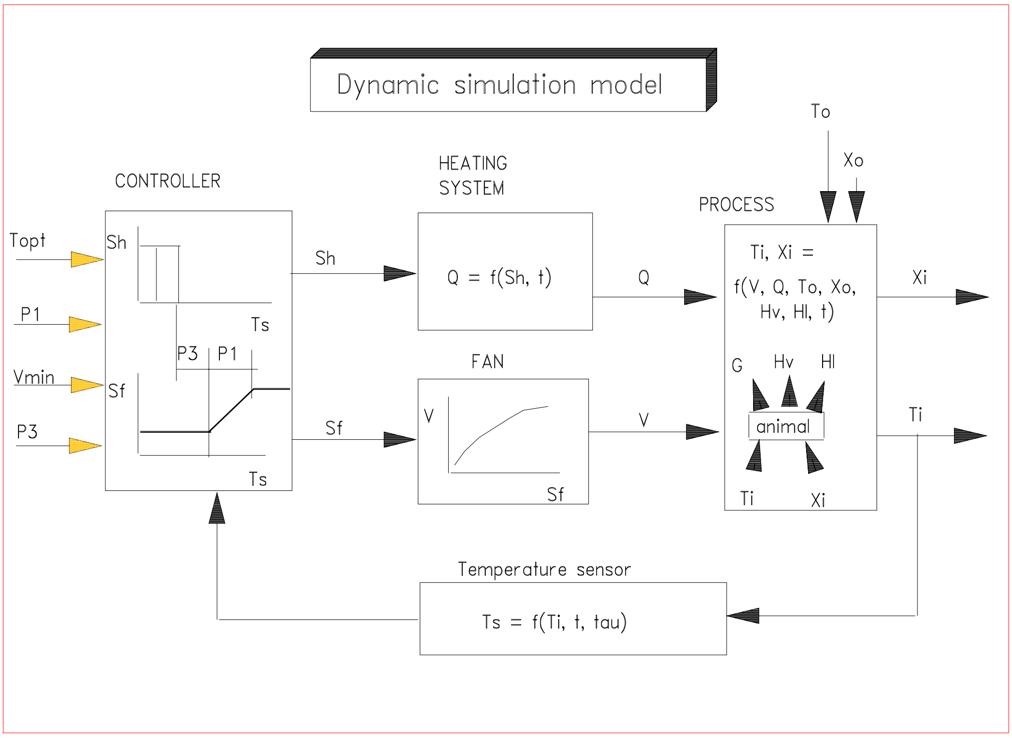

*Figure 1: The different sub models of the climate simulation model*

### 3.1.1 Process

Within the sub model of the process inside temperature, humidity and CO2-concentration is calculated, based on the controlled inputs of heat from the heating element (Q) and the amount of fresh air brought into the building by an axial fan (V). Disturbance variables are the outside climatic conditions (temperature, humidity, CO2-concentration), that are obtained from a dynamic reference year.

Heat, moisture and gasses are produced by the animals and the manure, and are evacuated from the building in different ways. Heat is loosed by convection and conduction through the building envelope and by ventilation. Moisture and gasses are assumed to be eliminated from the building only by means of the ventilation system.

### Building envelope

The considered building is a compartment for 80 fattening pigs which is surrounded by two identical compartments (figure 2). The compartment is divided into 10 pens, giving place to 8 pigs each. Thermal losses are calculated for the roof, the outside walls and the floor, each with its own heat conduction coefficient k. Heat losses to neighbourhood compartments are neglected since they are assumed to have an identical inside temperature.

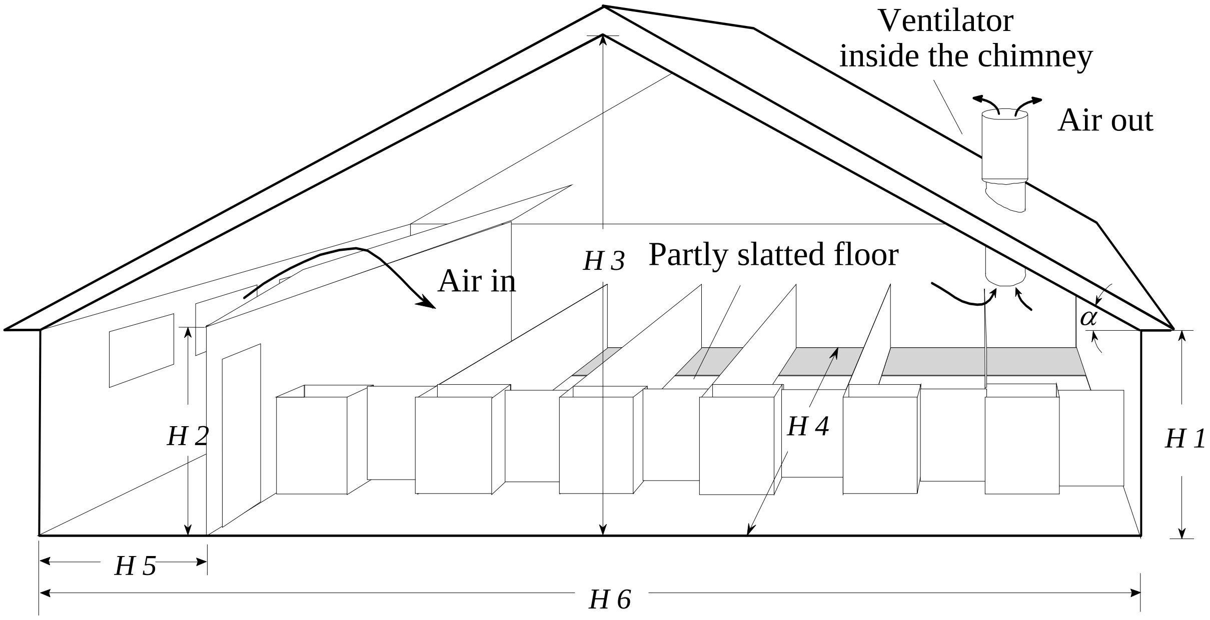

*Figure 2: The compartment of a livestock building as used in the program*

## The outside climate

In order to determine ***outside temperature and relative humidity*** the program uses a ***dynamic reference year*** for Belgium. This is obtained from hourly observations over fourteen years of climatic measurements (Dogniaux et al., 1980). By fitting a Fourier regression through these observations a smooth continuous function is obtained and temperature and humidity can be calculated at any time step.
Each day of the year has its own set of Fourier coefficients: this means the program has to read new coefficients out of a data file each time a day is computed.

The same procedure is followed for the outside relative humidity $RH_o$. The relative humidity is converted into the absolute value (kg water/kg dry air):

$$X_o = 0.622 \frac{RH_o \ p_{vsat}}{p - RH_o \ p_{vsat}}$$

In this equation p is the normal outside pressure (101325 Pa); $p_{vsat}$, the saturated vapour pressure as a function of temperature.

The ***outside CO2-concentration*** is assumed to be constant over a whole year period (360 ppm).

**The animal heat production**

The well established model of Bruce and Clark is used to determine the sensible and latent heat production of the animals below the critical temperature and within the thermoneutral zone (Bruce J.M., Clark J.J., 1979). The model variables are: air temperature, air velocity, floor type, live weight, and group size.

As a first input variable the animal weight M has to be known. The 80 animals in the compartment start at 20 kg and grow until 105 kg. The length of the fattening period is 140 days. During simulation, the animal weight is calculated from a growth curve.

Once the sensible and latent heat productions at both upper and lower critical temperature are known, they can be derived for any other temperature within the thermoneutral zone by interpolation or extrapolation.

The Bruce and Clarck model is a steady state model. To calculate the heat production as a function of time, the animal is assumed to act as a first order system to temperature variations. This is based on the idea that the animal will not waste energy by reacting as a higher order system (Berckmans, 1986).

To obtain the dynamic heat production as a function of time, a first order system is applied to the static acquired animal heat production:

**Inside temperature, Humidity and Gas concentration**

The dynamic mass and energy balances are used to determine the inside temperature, relative humidity and CO2- concentration.

***-inside humidity***:

$$\frac{dX_i}{dt} = -\frac{\gamma_{ao}}{\gamma_{ai}}\frac{V}{SV} X_i + \frac{\gamma_{ao}}{\gamma_{ai}}\frac{V}{SV} X_o + \frac{H_L N}{SV \gamma_{ai} \varepsilon_i}$$

This equation was derived from the moisture balance.

***-enthalpy of the inside air:***

$$\frac{dh_i}{dt} = \frac{\gamma_{ao}}{\gamma_{ai}} \frac{V}{SV} (h_o - h_i) - \frac{HL}{\gamma_{ai} SV} + \frac{H_L N + H_S N + Q_S}{\gamma_{ai} SV}$$

$$\text{with } h_o - h_i = c_a (T_o - T_i) + \varepsilon (X_o - X_i) + c_v (T_o X_o - T_i X_i)$$

This is the energy balance for the stable compartment.

***- $CO_2$-concentration***:

$$\frac{d[CO_2]}{dt} = \frac{V([CO_2]_o - [CO_2]_i + CO_{2-prod}}{S.V}$$

and (CIGR, 1984)

where $CO_2$-prod = 0.163($H_L$ +$H_S$)

These equations use the total volume of the compartment in the assumption of a perfectly mixed air space

### 3.1.2 The heating system

The heating element installed in the compartment is a convective water to air heat exchanger. There are two aspects of the heating system which need to be modelled: the energy use ***of the heat exchanger*** ($Q_U$) and the ***heat supplied*** by the same heat exchanger ($Q_S$).

In order to approach reality as good as possible the energy use of a heating element was measured at discrete time steps and a Fourier regression was fitted trough these points.

Total energy use and heat supply (in kWh) is achieved by cumulative addition of the values in each time step.

### 3.1.3 The ventilation system

Since the air flow rate is controlled by the voltage supplied to a fan the model consists of the relationship between air flow rate and voltage (figure 3). The disturbing variable is the differential pressure over the fan. The steady state fan data are measured at a laboratory test rig (Randall et al., 1996). The pressure difference over the fan is the result of the fan pressure and the building pressure characteristic, as illustrated with the corrected curve on figure 3. The dynamic pressure field over the fan is influenced by wind action on the building. Since the development of a new and accurate air flow rate sensor, that has been integrated in the feed-back control loop of a ventilation rate controller, wind effects on the ventilation rate can be totally eliminated (Vranken et al., 1996).

It has been shown by laboratory experiments that the behaviour of an axial fan can be described by a first order system. The time constant of the fan is about 2 seconds (De Moor et al., 1992).

The total energy use of the fan by summation of the consumed fan power over all the time steps.

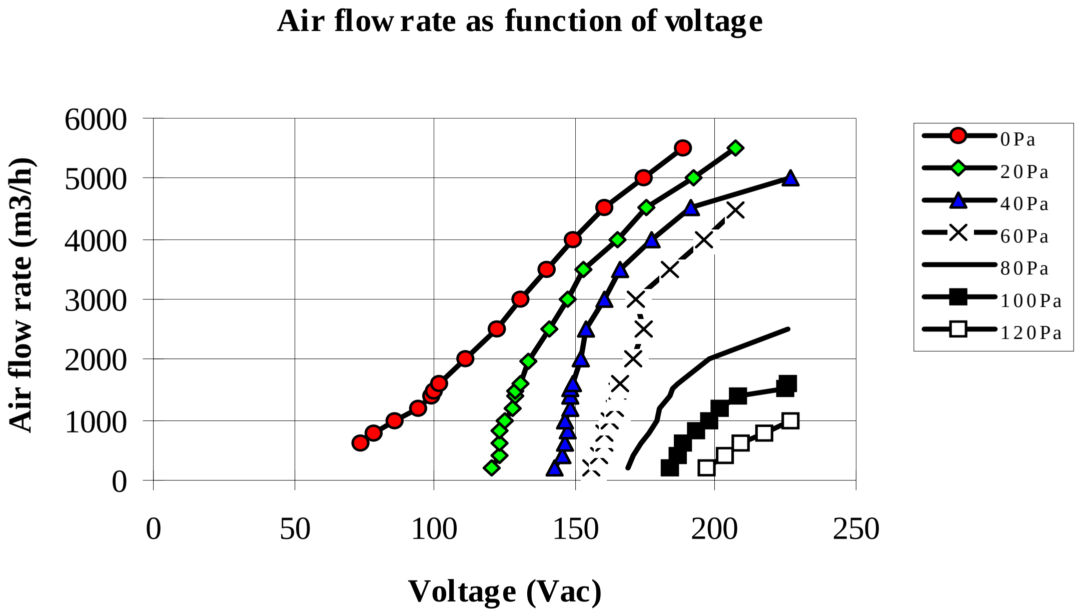

*Figure 3: The relation between airflow rate and voltage to the fan for different differential pressures.*

### 3.1.4 The temperature sensor

The input variable of the controller is the sensor temperature $T_s$ which measures the real inside temperature $T_i$ with a time delay according to the step response of a first order system:
There are two different time constants, depending on whether temperature is rising or falling.

### 3.1.5 The temperature controller

The temperature controller is an important submodel: it determines the ventilation rate applied and the heat supply. The program was developed to test all kinds of control algorithms: by manipulating this unit the algorithm can be changed easily.

Figure 4 shows a graphical representation of the reference control algorithm and a tested new algorithm. In the traditional algorithm the setpoint temperature is fixed at a value of 2°C above the lower critical temperature, and the proportional band was fixed at 3.5°C.
In the new algorithm it was tried to reduce the temperature fluctuations in the house by using a larger neutral zone (temperature difference between heating and ventilation setpoint), and by making the proportional band function of the outside temperature and the animal heat production.

Once all the setpoints are set the task of the controller is to control the ventilation rate and to change the heating on or off.
The controller reads the setpoints $V_{min}$, $V_{max}$ and $T_{opt}$ out of user definable curves (10 points) and interpolates for the present simulation time; in the next step the necessary corrections are performed. Other parameters are obtained using the appropriate function equations.

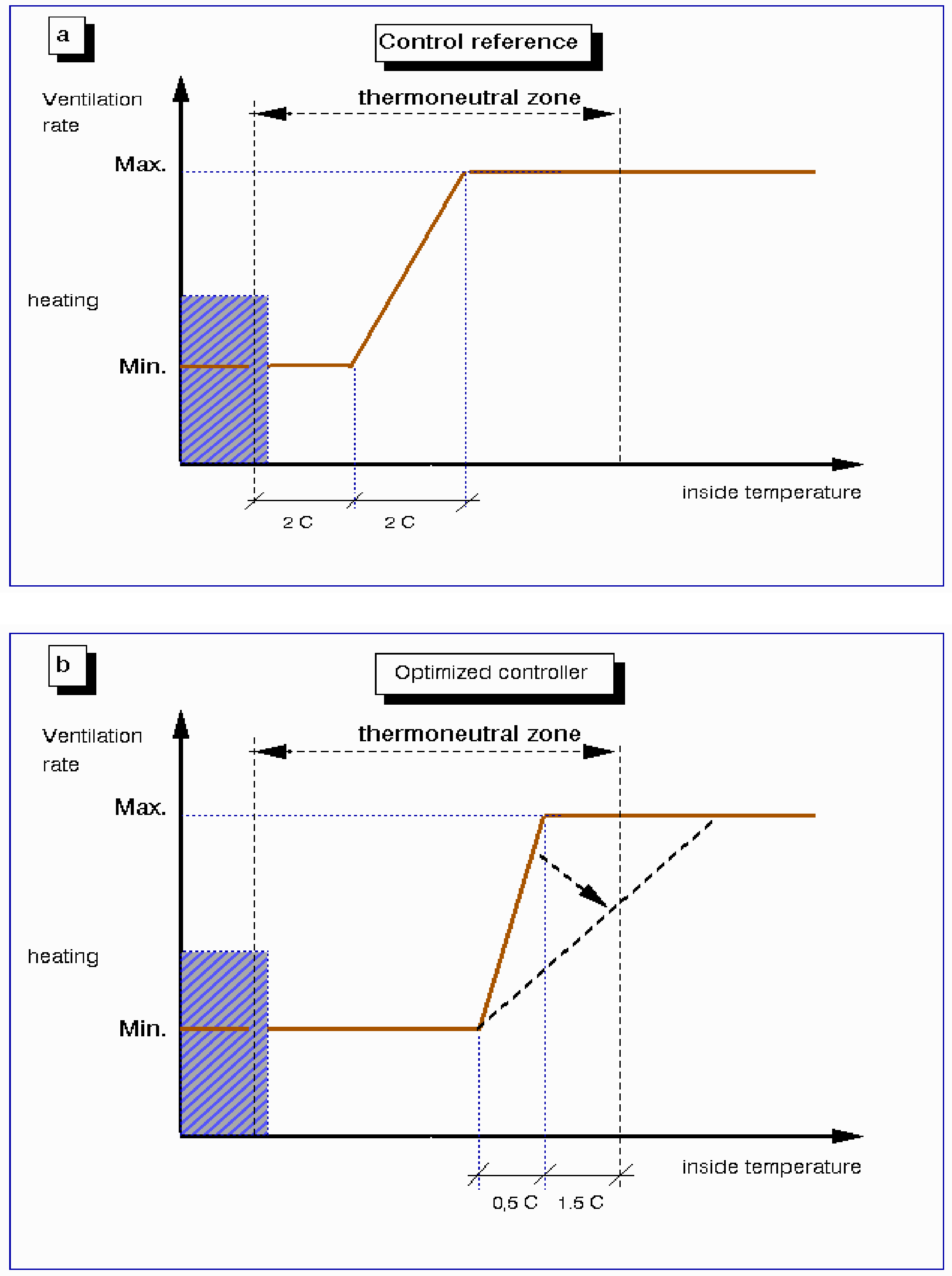

*Figure 4: The reference (a) and optimized (b) control algorithm*

### 3.1.6. Ammonia emission

To estimate the ammonia emission from pig houses, a mathematical simulation model has been developed (Figure 5, Berckmans et al., 1994; Ni et al., 1994). The source of ammonia is the manure produced by the pigs. From the nitrogen intake of the animals respectively 50% and 20% is excreted as urea and organic nitrogen components (faeces). Urea is hydrolysed to $NH_3$ and $CO_2$. This reaction is catalysed by the enzyme urease, which is produced by bacteria in the faeces.

The manure production is determined by the number and weight of the animals. The ammonia release from the manure is affected by the manure temperature, the surface of the manure pit, the dry matter content of the manure, the air velocity above the manure surface and the manure pH.

At lower ventilation rates the air velocity above the manure will be lower (reducing effect on ammonia emission), but at the other hand the stable temperature will be higher (higher risk on dirty laying areas) as well as the manure temperature (more ammonia emission).

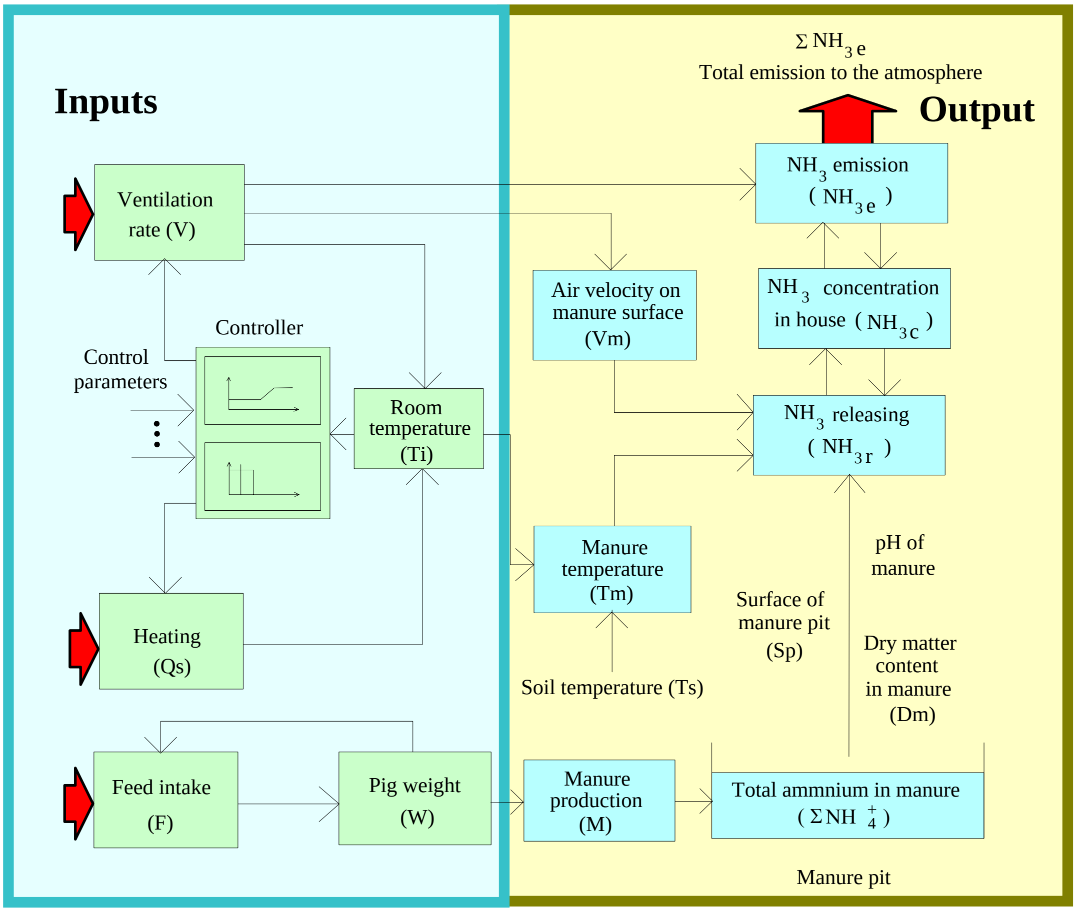

*Figure 5: The ammonia emission simulation model (Ni et al., 1994)*

## 4. Results and Discussion

## 4.1. Simulation output

The latest version of the simulation model is written in a SIMULINK 1.2 c version. For every time-step during the simulation, the following variables are written into a file: inside and outside temperature, inside and outside humidity, inside CO2-concentration, ventilation rate, heat supply, sensible and latent heat production, wall and heat losses, energy consumption for heating and ventilation, ammonia concentration and emission.

A simulation time step of 3 seconds was used, because this was the best compromise between the smallest time constant of the system (the fan with a time constant of 2 seconds) and the total simulation time (a whole year).

For all the variables hourly averages are made and the results are presented in tables and frequency diagrams.

## 4.2. New versus reference control algorithm

The traditional control settings (reference algorithm) do have the disadvantage to result in relative high temperature fluctuations, an unstable airflow pattern, high energy use for heating and ventilation, and an enormous output of wasteful gaseous products..

In an attempt to find a more appropriate control algorithm, several control settings and control algorithms have been simulated.

As a result from this analysis, a new control algorithm (NEW) for livestock buildings has been developed. The new algorithm is also based on a temperature proportional control algorithm, because this offers the possibilities to integrate it into existing climate control equipment. The main difference with a traditional ventilation controller, is that the setpoints are calculated automatically as a function of animal and climatic data.

The main differences in controller settings are presented in table 1.

| | Reference | New |
|---|---|---|
| Optimal temperature 20kg | 22°C | 25.5°C |
| 100kg | 17.5°C | 20.5°C |
| Min. ventilation 20 kg | 800 m3/h | 640 m3/h |
| 100 kg | | |
| Proportional band | 3.5°C | 0.5 -> 15°C |

*Table 1: Different control settings between reference and new control algorithm*

A simulation run was done to compare this new control algorithm with the reference controller as shown. In Table 2 the simulation results are summarised for the whole reference year.

| | Reference | New |
|---|---|---|
| Average inside temperature | 19.7°C | 21.2°C |
| Temperature range | 16.2 - 31.5°C | 16.8 - 31.5°C |
| Average temp.fluctuation | | |
| over 2 hours | 0.29°C | 0.21°C |
| over 6 hours | 0.74°C | 0.53°C |
| Temperature within comfort zone | 95,2% of time | 95.2% of time |
| Average ventilation rate | 2686 $m^3/h$ | 1804 $m^3/h$ |
| Ventilation rate range | 795 - 5750 $m^3/h$ | 635 - 5750 $m^3/h$ |
| Average $CO_2$-concentration | 1.37 $l/m^3$ | 1.79 $l/m^3$ |
| CO2 -range | 0.54 - 1.98 $l/m^3$ | 0.55 - 2.34 $l/m^3$ |
| Total ammonia emission | 108 kg | 100 kg |
| Energy use | | |
| Heating | 2901 Kwh | 1217 Kwh |
| Ventilation | 2068 Kwh | 1685 Kwh |

*Table 2: Comparison of simulation results between two control algorithms*

It can be concluded that the **average ventilation rate** is decreased from 2686 m3/h to 1804 $m^3/h$, corresponding to a reduction of 32 % on a yearly base. This lower ventilation rate results in a relative higher internal temperature. However, the calculated internal temperature does not exceed the upper level of the animals comfort zone in a higher extend than the reference controller (during 4.8% of time too warm). This means that the building temperature has changed within the limits of the thermal comfort zone, but it can be expected that there is no significant (negative) effect on the production results (feed conversion ratio, growth rate, ...)

The **average temperature fluctuations** over a 6 hours period are reduced from 0.74 °C to 0.53 °C, which is a reduction of about 30%. In the reference controller, during 12% of time the temperature difference over 6 hours was more than 1°C, while in the new controller this is less than 6 % of time. This can be explained by the fact that the ventilation rate in the new control algorithm is calculated with a heat balance method in such a way that the ventilation heat losses correspond to the sensible heat production of the animals. In the reference controller, the ventilation rate is only determined by the measured internal temperature.

Another big advantage of the new control algorithm is the **reduced risk for cold draught** on the animals. Especially at the end of a sunny day, the ventilation rate can be at its maximum capacity, while the incoming air is cooling down. Under these conditions a lot of relative cold air in brought into the building, resulting in unfavorite conditions and respiratory diseases. This problem is completely solved in the new algorithm, because the ventilation rate is automatically reduced if the outside temperature is decreasing.

The **maximum $CO_2$ concentration** is increased from 1.98 $l/m^3$ to 2.34 $l/m^3$ or an increase with about 20 %. This can be explained by a reduction of the minimum ventilation rate in the new control algorithm. Since the availability of a new and accurate ventilation rate controller (Vranken et al., 1996) it is indeed possible to reduce the ventilation rate under field conditions, without the risk of insufficient fresh air supply. The minimum ventilation rate setpoint is based on the CIGR-recommandations of maximum 2.5 l/m$^3$ internal $CO_2$ (CIGR, 1984).

The lower ventilation rate does also have a positive effect on **the energy use**. The heat consumption was reduced from 2901 Kwh to 1217 Kwh, a reduction of about 40%, while the simulated energy use for ventilation was reduced with about 10%

The simulated **ammonia emission** was reduced with about 8% on a yearly base. This mainly caused by the lower ventilation rate, keeping more ammonia inside the building and lowering the air velocity above the manure. The resulting inside ammonia concentration was higher with the new control algorithm (13.2 versus 9.1 PPM), but never exceeded the tolerance level of 25 PPM.

### 4.3. Model validation

As stated in the objectives measurements have been done in a commercial livestock building to validate the dynamic model. The question is how reliable such a complex model (different sub models) is in comparison with reality and what scale of agreement one can expect with field measurements. In this paper some results are given but for more validation data we refer to previous literature (Berckmans et al., 1986; Berckmans et al., 1994).

During 3 years temperature and ventilation rate data were continuously measured with a sample frequency of 2 minutes in 8 commercial pig houses all over the country.

For one pig house, identical to the one described in paragraph 2, some data of simulated temperature are plotted against the measured data for a one week period going from 1 - 5 November 1990. To do this comparison the measured outside temperature was used in the simulation model in stead of the value from the reference year. An earlier data-set of the same building was used for parameter estimation.
It can be seen that there is an acceptable agreement (mean difference of 0.37 ° Celsius) between the simulated and measured inside temperature and this although the simulated and measured ventilation rate do not agree that well. The mean difference between simulated and measured ventilation rate is about 250 m$^3$/h.
In general one might come to the conclusion that the agreement between such a complex model and measurements in field situation is rather good. Between all the authors who used the identical equations, the few among them who recently did a comparison with field measurements had this type of conclusion. Gates et al. (1992) concluded from measurements in a test broiler house that the transient response of spatially dependent inside temperature agreed reasonably with measured temperatures. Zhang et al. (1992) found good agreement in a laboratory test chamber.

In figure 7 the temperature as measured at two different positions within the volume of the livestock building are plotted as a function of time. The two different positions of the temperature sensors are marked in Figure 2.

It can be noticed that the difference between two sensors at different positions within the building volume is much higher (mean value of 0.92 ° Celsius) than the difference between the simulated and the measured value at another position.
In other words the basic assumption of a perfectly mixed air volume without temperature gradients does not hold at all. One might always find a position of the

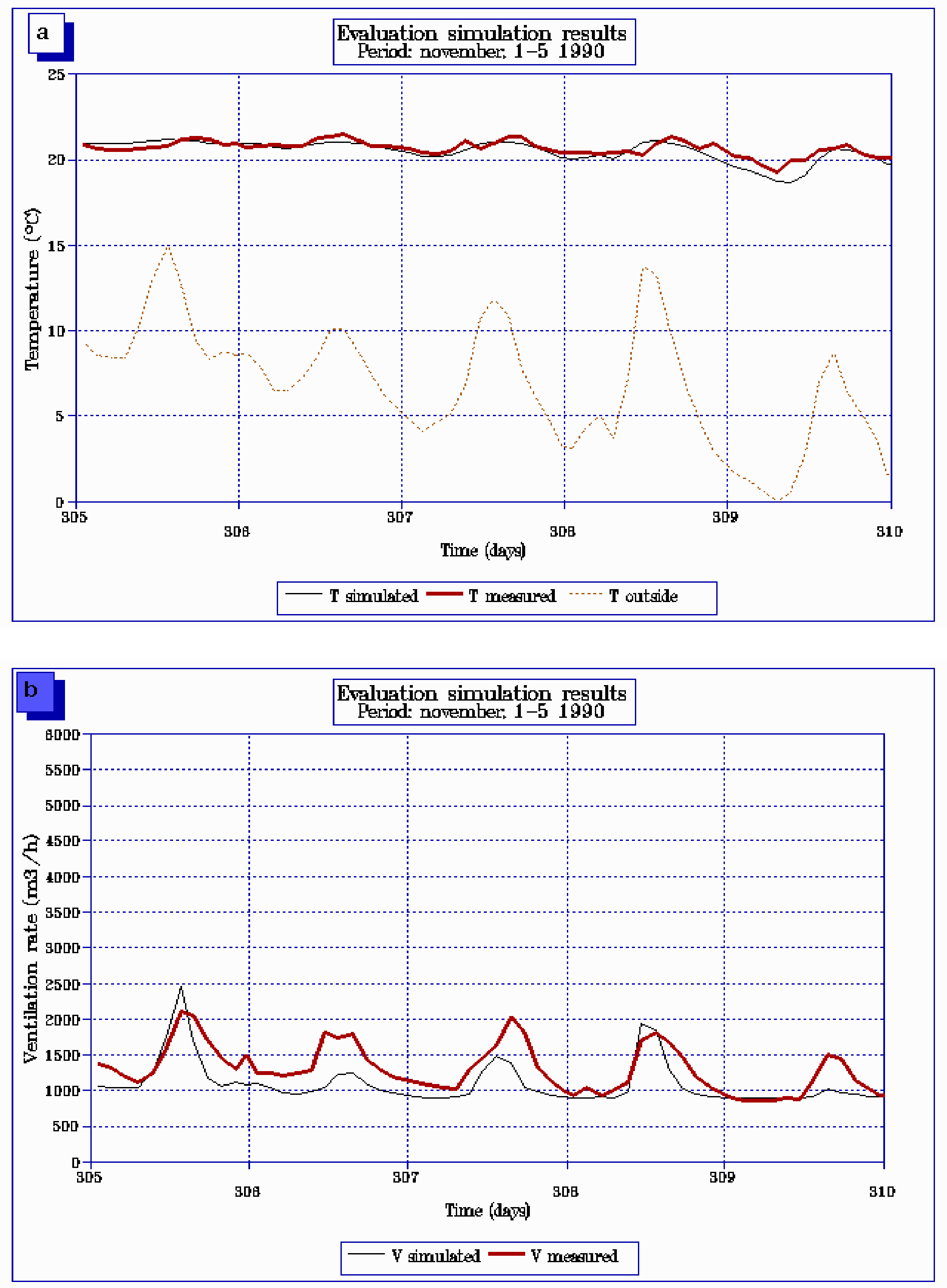

*Figure 6: Simulated and measured inside temperature (a) and ventilation rate (b) over a 5 days period in a compartment with 80 pigs*

temperature within the imperfectly mixed space where the simulation model does apply rather good, even when the ventilation rate has not been simulated with high accuracy.

The consequence however is that one must wander how far the connection between the simulated temperature and the heat production of the animals is realistic. To study this process more knowledge is required about the transportation of energy and mass around the living organism. A model concept to model the imperfectly mixed air space has been presented in literature (Berckmans, 1986; Berckmans and De Moor, 1992; De Moor and Berckmans, 1996) but today it still is impossible to use this method for simulation purposes.
To compare different control strategies and to develop new controllers in an efficient way the type of modelling as presented here still remains the best available method.

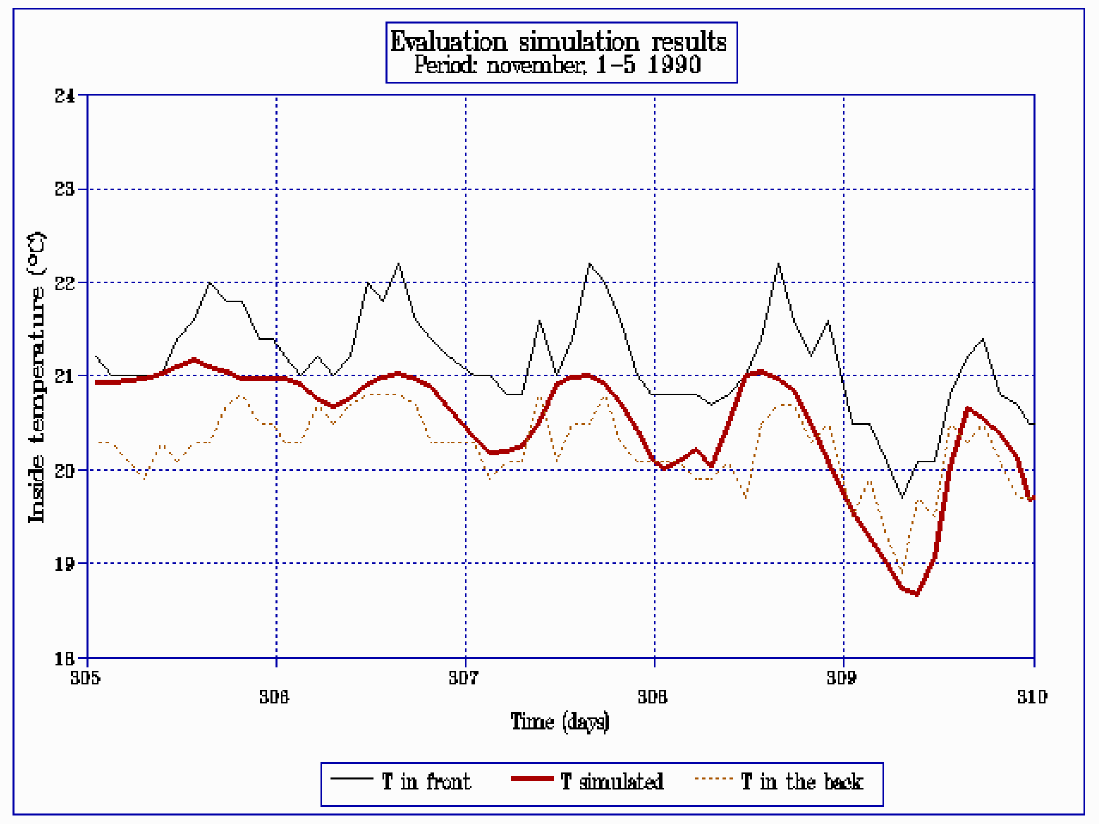

*Figure 7: Measured temperature difference and simulated inside temperature in a 5.2m x 13.5 m compartment for fattening pigs (position of the sensors on figure 2: $t_1$ = T in front; $t_2$ = T in the back).*

## 5 Conclusions

A simulation model to evaluate new climate control algorithms for livestock buildings has been built and validated.
Such a simulation model allows to estimate the efficiency of different control strategies and by doing so to develop new controllers.
By applying this simulation technique, a new control algorithm for fattening pig houses has been designed, and has the following advantages compared to the control algorithms as they are used today (yearly base):

- 40 % lower energy use for heating
- 30 % lower temperature fluctuations
- reduced risk for cold draughts on the animals
- about 8% lower ammonia emission

In a validation experiment the agreement between the simulated and the measured temperature is surprisingly good when taking into account the complexity of the simulated process and the required sub models to simulate such a system. In agreement with other authors the mean difference between simulated and measured temperature was 0.37 Degree Celsius.
The basic assumption of perfectly mixing does not hold at all in reality. The difference between the measured temperature at different positions within the imperfectly mixed air volume is higher than the differences between the simulated and measured temperature. Consequently one has to be careful when making conclusions based on this type of simulations. It might always be possible to find a position where the simulation output does apply.
More knowledge is needed about the process of three dimensional energy and mass transportation around a living organism.

## 6. Notation

$\gamma_{ai}$, $\gamma_{ao}$: Density of inside and outside air [kg/m$^3$]
$\varepsilon$, $\varepsilon_i$: Evaporation heat of water [J/kg]
$c_a$: Specific heat of dry air at constant volume [J/kg.K]
$c_V$: Specific heat of vapour [J/kg.K]
$h_i$, $h_o$: Inside and outside air enthalpy [J/kg]
$CO_2$: $CO_2$-concentration [l/m$^3$]
$H_L$: Latent heat production [W]
$H_S$: Sensible heat production [W]
H1: Height of the outside wall of the pig house compartment (m)
H2: Height of the internal wall between feeding allee and compartment (m)
H3: Height of the ridge (m)
H4: Width of the pig house compartment (m)
H5: Depth of the pig house compartment (m)
H
N: Number of animals in the house
p: Normal outside pressure [101325 Pa]

$p_{vsat}$: saturate vapor pressure [Pa]
Q, Qs: Heat supply of heating element [W]
$RH_o$: Outside relative humidity [%RH]
SV: Building volume [$m^3$]
$t_1$, $t_2$: Position of temperature sensors in the pig house compartment
$T_o$,$T_i$: Outside and inside temperature [°C]
$T_s$: Sensor temperature [°C]
$X_o$: Outside humidity ratio [kg $H_20$/kg dry air]
$X_i$: Inside humidity ratio [kg $H_20$/kg dry air]
V: Air flow rate [$m^3$/h]

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