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COMMISSION OF THE EUROPEAN COMMUNITIES

SYSTEM SIMULATION IN BUILDINGS

Proceedings of an International Conference

hosted by

University of Liège, Château Colonster
Liège, Belgium
December 1-3, 1986

PROCEEDINGS OF THE SECOND INTERNATIONAL CONFERENCE ON SYSTEM SIMULATION IN BUILDINGS
Liège , dec. 1986, Section 6.3 , pag. 369 - 388.

1987

EC ENERGY R + D PROGRAMME

MODELLING STRATEGY FOR PERFORMANCE ESTIMATION OF CONTROL SYSTEMS IN CONFINED SPACES

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Summary

A model is presented that can be used in evaluation of different control strategies for the resulting inside climate and the global energy use of ventilated spaces. In published work the room air is considered to be perfectly mixed, the air flow rate is supposed to be constant or to vary linearly with temperature. In this work the model is based on following assumptions : there is a non-perfectly mixed air space, the air flow pattern is supposed to be controlled accordingly to the criterion of the Corrected Archimedesnumber, the ventilating rate can change as a non-linear function of inside temperature.

In order to get rid of the non-uniform distribution of temperature and humidity, a lumped parameter model is set up that simulates the local climate concentrated around the fixed position(s) of the sensor(s). This model consists of a set of bilinear differential equations, which describe the transient behaviour of temperature and humidity. The local inputs of the model are estimated using the numerically robuust technique of the singular value decomposition. The result is a very compact model that can be used as an adaptive on-line algorithm.

1. Introduction

In several applications of climatic control, there is a great internal production of gases, heat and moisture within the confined space such as in modern livestock buildings, greenhouses, industrial spaces, space stations, ... In these confined spaces the global ventilating rate and the (positive or negative) heat supply to the space are the control inputs to regulate inside climate (temperature, humidity, gasconcentration). The importance of a good control of these inputs in order to optimize the inside climate and to minimize the global energy use has been described (1, 2, 3, 4). Moreover in some typical applications, such as in modern pig houses, the internal gas-, heat, and moisture production of living creatures and the desired inside climatic conditions are time varying (due to bio-cycle, age, activity, external climatic conditions, ...). A modern pig house, in which the free-cooling principle is used, can be considered as a more general case of those applications.

Although a lot of modern hardware is used in those spaces, actual control equipment seems not to contain more advanced control algorithms (5). As compared to buildings without control equipment, modern pig houses in general don't give the expected improvement of the production results (6, 7). The main objective of using control strategies in this application is to control the inside climate by regulating the control inputs : the ventilating rate $\dot{V}$ through the global space, the heat supply Q to the space and the air flow pattern (figure 2). The second objective of using control strategies in this application is to minimize the energy use : the heat supply of the heating system, the electricity use of the ventilating system and the feed intake by the animals. As a consequence of these objectives, a model for performance estimation of control systems in these applications should permit to study the response of the inside temperature and humidity to the control inputs as they are generated by the control system and to calculate the corresponding energy use.

In literature several simulation models have been proposed to study the short term behaviour of inside climate. In published models to study the inside climate in (livestock) buildings the following assumptions are made (8,9,10,11,12) :

- it is supposed that there is a perfectly mixed air volume in the space ;
- the inside temperature and humidity are considered to be homogeneous in the air volume ;
- the air flow rate is considered to be constant or to vary linearly as a function of inside temperature ;
- no further assumptions are made concerning the air flow pattern.

It has been shown however that the assumptions of a perfectly mixed airspace and of a constant ventilating rate do not hold anymore in those applications (13,14,15). Furthermore it has been proven that the influence of the air flow pattern is of crucial importance for the resulting inside climate (13,15).

1. Objective

From the problem posed in the introduction it can be seen that the most difficult part of a global model for performance estimation of control systems in those applications, is the submodel that describes the response of the inside climate to the higher mentioned process inputs. To become a model that is usable for performance estimation of control systems for ventilated confined spaces, the model has to simulate the high-frequency behaviour of inside climate in a non-perfectly mixed air space. The importance of air flow rate and air flow pattern in those applications has been stated while the constant air flow rate assumption does not hold in applications with free-cooling (7,12,13,14). The first objective is to present a mathematical model to simulate the response of inside temperature and humidity in a confined space. Instead of the usual hypotheses of : a perfectly mixed airspace, a homogeneous inside humidity and temperature, an air flow rate that is considered to be constant or very linearly with inside temperature and no further assumptions about the air flow pattern ; a new approach is proposed. As contrasted to these usual hypotheses, in this model the following hypotheses are made :

- there is no perfectly mixed air in the space ;
- as a consequence there are differences in inside temperatures and humidities ;
- the air flow pattern is considered to be controlled accordingly to the criterion of the Corrected Archimedes Number (16,17).

A model is set up that models the local climate concentrated around the fixed position(s) of the control systems' sensor(s). The main problem to apply this model-concept is the estimation of the local inputs of this model. The more specific objective of this paper is to show the identification procedure that has been applied to identify these local inputs.

3. Method

The global simulation model consists of different submodels that describe the behaviour of the subsystems as shown in figure 1 (18). As mentioned before, the most difficult part is the submodel that models the response of inside temperature and humidity to the process inputs : ventilating rate $\dot{V}$ and heat supply Q. As can be seen from figure 1, the inside climate (temperature and humidity) can in this case be defined as the temperature and the humidity as they are measured by the sensor(s) of the control system. In order to get rid of the non-uniform distribution of temperature and humidity in the non-perfectly mixed airspace, the following concept is used. Although the non-perfectly mixed air in the global space, there always can be defined a control volume as the volume that is enveloping the temperature sensor and in which there is at the same time a perfectly mixed air volume. From theoretical viewpoint this control volume is considered to be infinite small but from measurements it can be seen that this control volume can be rather great for certain values of the process inputs (18). In this concept there are two types of inputs (figure 2) : firstly the global inputs of the process : the ventilating rate $\dot{V}$, the global heat flow to the process ($Q_h + Q_{animal} + Q_{envelope}$) and the global moisture production $\dot{E}$ from the animals. Secondly there are the local inputs of the control volume (figure 2) : the part of the global heat flow that enters in the control volume, Q_{cv} ; the part of the global ventilating rate that enters in the control volume, $\dot{V}_{cv}$; and the part of the global moisture production that enters in the control volume, $\dot{E}_{cv}$. Since there is a perfectly mixed air space in the control volume, the well-known physical laws (mass balance, energy balance) can be applied on this control volume and its local inputs. In this way a set of bilinear differential equations can be deducted that describe the transient behaviour of temperature and humidity in the control volume that is enveloping the sensor of the control system (18).

$$\left.\begin{aligned} \frac{dw_{in}}{d\tau} &= - C_1 \cdot \dot{v}_{cv} \cdot w_{in} + C_1 \cdot \dot{v}_{cv} \cdot w_{out} + C_3 \cdot \dot{e}_{cv} \\ \frac{dt_{in}}{d\tau} &= - C_2 \cdot \dot{v}_{cv} \cdot t_{in} + C_2 \cdot \dot{v}_{cv} \cdot t_{out} + C_4 \cdot \dot{q}_{cv} \end{aligned}\right| \qquad (1)$$

From the application of the physical laws and the mathematical deduction which results in set (1), the physical meaning of the parameters in these equations is known (18). The parameters C_1, C_2 and C_4 are combining well-known physical characteristics as explained in the list of symbols and therefore they can be considered as physical constants (18). In the same way it can be deducted that the parameters $\dot{v}_{cv}$, $\dot{e}_{cv}$ and $\dot{q}_{cv}$ do have a physical meaning (18). $\dot{v}_{cv}$ is the volumetric concentration of fresh air flow rate in the control volume or

$$\dot{v}_{cv} = \frac{\dot{V}_{cv}}{\text{volume of the control volume}} \qquad (m^3.s^{-1}.m^{-3})$$

In the same way $\dot{q}_{cv}$ is the volumetric concentration of heat flow in the control volume and $\dot{e}_{cv}$ is the volumetric concentration of moisture flow in the control volume.

The three unknown parameters, that cannot be measured, are

$$\dot{v}_{cv},\ \dot{e}_{cv} \text{ and } \dot{q}_{cv}$$

If it is taken into account that :

$$\left.\begin{aligned} B_1 &= - C_1 \cdot \dot{v}_{cv} \\ B_3 &= C_1 \cdot \dot{v}_{cv} \cdot w_{out} + C_3 \cdot \dot{e}_{cv} \\ B_2 &= - C_2 \cdot \dot{v}_{cv} \\ B_4 &= \dot{v}_{cv} \cdot t_{out} + C_4 \cdot \dot{q}_{cv} \end{aligned}\right| \qquad (2)$$

and

$$\left.\begin{aligned} K_1 &= \frac{C_3 \cdot \dot{e}_{cv}}{C_1 \cdot \dot{v}_{cv}} \\ K_2 &= \frac{C_4 \cdot \dot{q}_{cv}}{C_2 \cdot \dot{v}_{cv}} \end{aligned}\right| \qquad (3)$$

Then it can be shown that the solution of the set of equation (1) in discrete time can be written as (14) :

$$\begin{bmatrix} 1 & w_{out(k)} & w_{in(k)} & w_{in(k+1)} \end{bmatrix} \cdot \begin{bmatrix} K_1 \cdot (1 - e^{B1.\Delta\tau}) \\ 1 - e^{B1.\Delta\tau} \\ e^{B1.\Delta\tau} \\ -1 \end{bmatrix} = 0$$

and

$$\begin{bmatrix} 1 & t_{out(k)} & t_{in(k)} & t_{in(k+1)} \end{bmatrix} \cdot \begin{bmatrix} K_2 \cdot (1 - e^{B2.\Delta\tau}) \\ 1 - e^{B2.\Delta\tau} \\ e^{B2.\Delta\tau} \\ -1 \end{bmatrix} = 0 \qquad (4)$$

where $\Delta\tau$ is the sampling period.

For different succeeding observations, $k = 0 \rightarrow (m - 1) \geqslant 4$ and if the assumption is made that B_1, B_2, K_1 en K_2 are constant over the time interval $0, n.\Delta\tau$, it can be written that :

$$\underbrace{\begin{bmatrix} 1 & w_{out(0)} & w_{in(0)} & w_{in(1)} \\ 1 & w_{out(1)} & w_{in(1)} & w_{in(2)} \\ \cdot & & & \\ \cdot & & & \\ 1 & w_{out(m-1)} & w_{in(m-1)} & w_{in(m)} \end{bmatrix}}_{m \times 4 \text{ matrix } (w)} \cdot \begin{bmatrix} K_1 \cdot (1 - e^{B1.\Delta\tau}) \\ 1 - e^{B1.\Delta\tau} \\ e^{B1.\Delta\tau} \\ -1 \end{bmatrix} = 0$$

and

$$\begin{bmatrix} 1 & t_{out(0)} & t_{in(0)} & t_{in(1)} \\ 1 & t_{out(1)} & t_{in(1)} & t_{in(2)} \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ 1 & t_{out(m-1)} & t_{in(m-1)} & t_{in(m)} \end{bmatrix} \cdot \begin{bmatrix} K_2 \cdot (1 - e^{B2.\Delta\tau}) \\ 1 - e^{B2.\Delta\tau} \\ e^{B2.\Delta\tau} \\ -1 \end{bmatrix} = 0 \qquad (5)$$

This means that if the collected data are really generated by a discrete time invariant system and if the data are without noise that (18) :

$$\text{rank} \begin{bmatrix} 1 & w_{out(0)} & w_{in(0)} & w_{in(1)} \\ \cdot & & & \\ \cdot & & & \\ 1 & w_{out(m-1)} & w_{in(m-1)} & w_{in(m)} \end{bmatrix} \leqslant 3$$

To become a unique solution, it is necessary that (18, 19, 20) :

$$\text{rank (matrix } w) = 3$$

In that case, it is shown by equation (4) that

$$\begin{bmatrix} K_1 \cdot (1 - e^{B1.\Delta\tau}) \\ 1 - e^{B1.\Delta\tau} \\ e^{B1.\Delta\tau} \\ -1 \end{bmatrix}$$ is the orthogonal complement of $\begin{bmatrix} 1 & w_{out(j)} & w_{in(j)} & w_{in(j+1)} \end{bmatrix}$

for $j = 0 \rightarrow (m-1)$ and $m \geqslant 4$.

The same can be said for the temperature equation. These orthogonal complements can be solved by the robuust technique of singular value decomposition (19, 20, 21). The singular values provide a quantitative measure for the rank of a matrix (19, 20). If the fourth singular value σ_4 of the m x 4 w-matrix is equal to 0 and if $\sigma_3 \neq 0$, then it can be proven that matrix w is close to a matrix of rank 2 and that the theoretically "unique" solution of the set of equation 5 will not be very stable.

From set (1) it follows that for a constant steady state situation :

$$w_{in\ constant} = w_{out} + \frac{C_3 . \dot{e}_{cv}}{C_1 . \dot{v}_{cv}} \qquad (7)$$

or

$$\underbrace{\begin{bmatrix} 1 & w_{out} & w_{in\ constant} & w_{in\ constant} \end{bmatrix}}_{\text{matrix } w_{con}} \cdot \begin{bmatrix} \frac{C_3 . \dot{e}_{cv}}{C_1 . \dot{v}_{cv}} & 0 \\ 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{bmatrix} = \begin{bmatrix} 0 \end{bmatrix}$$

Equation (7) shows that $w_{in\ constant}$ is a linear combination of column one and two in the matrix w_{con} while column three and four are equal. This means that :

$$\text{rank } (w_{con}) = 2 \text{ or also } \sigma_3 = 0$$

It can be concluded that if the system reaches a constant steady state after dynamic behaviour, then the third singular value of the w-matrix, σ_3 will decrease. Hence σ_3 can be considered as a measure for the dynamics in the signal. If σ_3 is large enough, then a unique stable solution of the set of equation will be the result. Hence, σ_3 is also a measure for the reliability of the identification. With noise on the data, also $\sigma_4 \neq 0$. The more noise energy is superimposed on the data, the larger will be σ_4.

One can state that the ratio $\frac{\sigma_3}{\sigma_4}$ is a measure for the $\frac{\text{signal dynamics}}{\text{noise energy}}$ and for the reliability (stability) of the identification results from noisy data.

As shown in figure 2, the value of $\frac{\sigma_3}{\sigma_4}$ will increase if the system is in a dynamic state and will decrease if the system reaches a constant steady state.

It can be concluded that the value of $\frac{\sigma_3}{\sigma_4}$ can be used as a criterion to find out wheather the signal dynamic to noise ratio is good enough to use the data for identification.

4. Results

Data have been collected on the real system by doing measurements in a commercial pig house in the field. As shown in figure 3 the process inputs global ventilating rate, $\dot{V}$; and global heat input by the heating system Q_h, have been measured. This while the air flow pattern was controlled accordingly to the criterion of the Corrected Archimedesnumber. The step response of the process outputs : inside temperture t_{in} and inside humidity w_{in} has been measured.

Measurements have been done for three levels of ventilating rate, three levels of heat supply Q_h and three levels of internal loads (heat and moisture production of the animals. From these measurements it could be concluded that an animal weight of 80 kg (high internal loads) is giving the most dynamic changes of inside temperature and of air flow pattern. For this weight of 80 kg, 18 different datasets have been selected for identification.

Such a dataset is covering a 4 hours period with a sample time of two minutes. In such a dataset, the data-parts that permit a robuust identification have been located by the $\frac{\sigma_3}{\sigma_4}$ -criterion (figure 4).

As mentioned higher, the three unknown local inputs in the model, $\dot{v}_{cv}$, $\dot{c}_{cv}$ and $\dot{w}_{cv}$ have been estimated using the technique of singular value decomposition. Figure 5 gives as an example the measured signal of the global inputs ventilating rate $\dot{V}$ and heat supply $\dot{Q}$. Figure 6 shows the local inputs $\dot{v}_{cv}$, $\dot{c}_{cv}$ and $\dot{w}_{cv}$ as they have been estimated. The fact that in this case the local input $\dot{v}_{cv}$ is increasing while the global input $\dot{V}$ is decreasing (figure 5) can be perfectly explained by the changes of the air flow pattern (18). Figure 7 gives a representative result as they were found on these 18 different data-sets, all of them for the animal weight of 80 kg. Each data-set had a different combination of input level of the global control inputs ventilating rate and heat supply. Temperature can be modelled with a mean accuracy of about 0,2°C and humidity with a mean accuracy of 0,007 kg H_2O/kg dry air.

5. Conclusions

A model that is based on physical laws and in which every parameter has a physical meaning, is proposed to calculate the inside climate in confined spaces. This model makes the assumption of a NON-perfectly mixed airspace. Furthermore the ventilating rate and the heat supply are supposed to change as a non-linear funciton of inside temperature.

To estimate the model-parameters the technique of singular value decomposition has been used. To locate the data-parts that can be used for identification, the $\frac{\sigma_3}{\sigma_4}$ criterion has been applied : $\frac{\sigma_3}{\sigma_4}$ is used to measure the ratio between signal dynamic and noise. Using this technique, the model gives results that are accurate enough to use the global model (figure 1) for evaluating control strategies. The process-model and the higher mentioned criterion are very compact and therefore they can be used as a basis for an on-line control-algorithm.

List of symbols

- C_1 : physical constant : ratio of the specific mass of the outside air and the inside air.
- C_2 : physical constant (14)
- C_3 : physical constant : inverse value of the product of the specific mass of inside air and the evaporation heat of water $(kg(water).m^3.J^{-1}.kg^{-1})$
- C_4 : physical constant : inverse value of the product of specific mass of inside air and the specific heat of inside air $(K.m^3.J^{-1})$
- e_{cv} : volumetric concentration of moisture flow in the control volume $(J.s^{-1}.m^{-3})$
- q_{cv} : volumetric concentration of heat flow rate in the control volume $(J.s^{-1}.m^{-3})$
- t_{in} : inside temperature at the location of the controller's temperature sensor (°C)
- t_{out} : outside temperature (°C)
- v_{cv} : volumetric concentration of fresh air flow rate in the control volume $(m^3.s^{-1}.m^{-3})$
- w_{in} : humidity ratio of inside moist air at the location of the controller's temperature sensor $(kg(water).kg^{-1}(air))$
- w_{out} : humidity ratio of outside moist air $(kg(water).kg^{-1}(dry\ air))$
- r : time (s).

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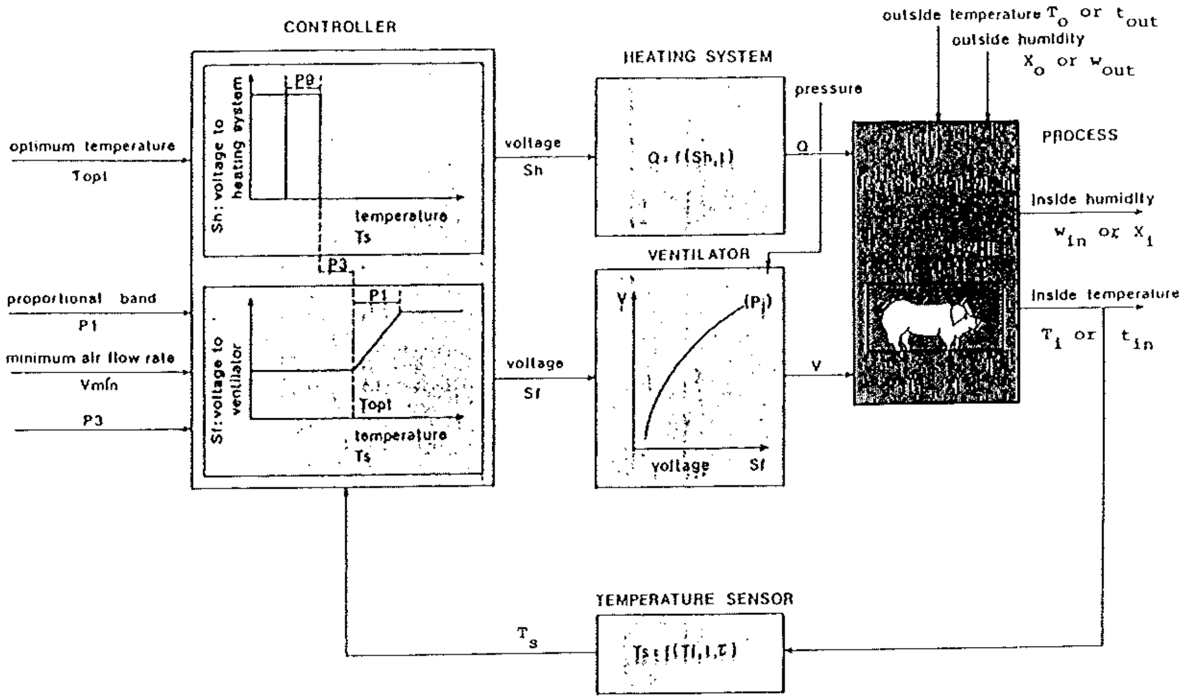


Figure 1 : Diagram of the global model.

MODELCONCEPT

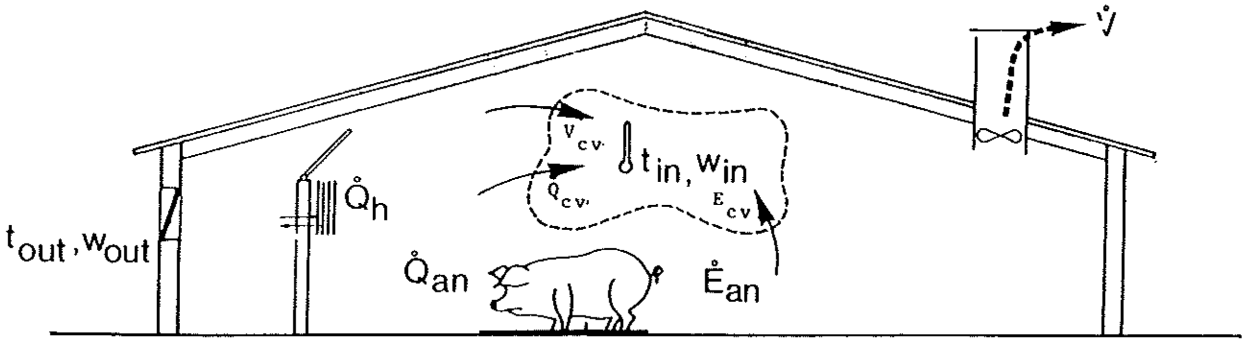


Figure 2 : Concept of the model based on physical laws.

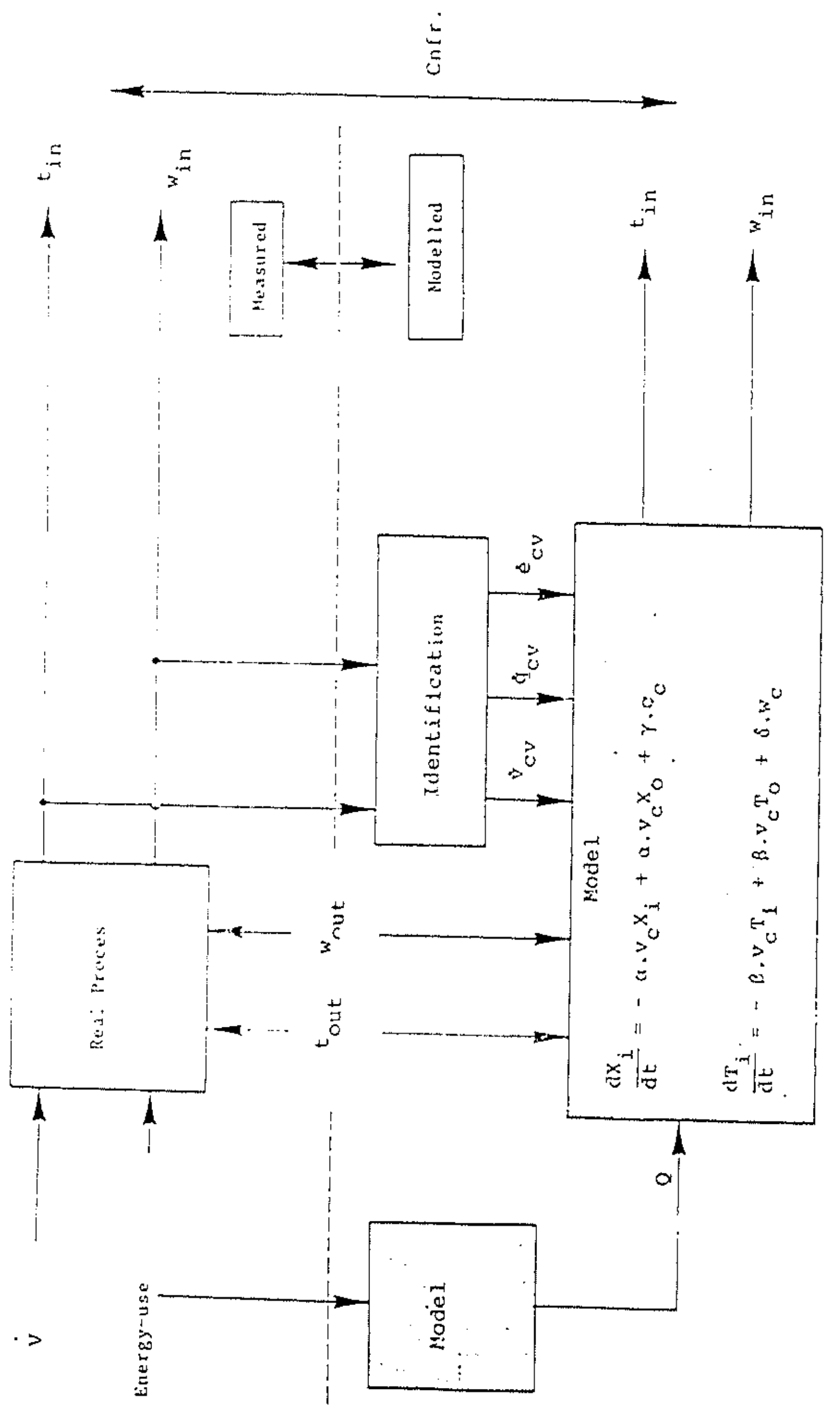


Figure 3 : Method to evaluate the model combined with the identification procedure

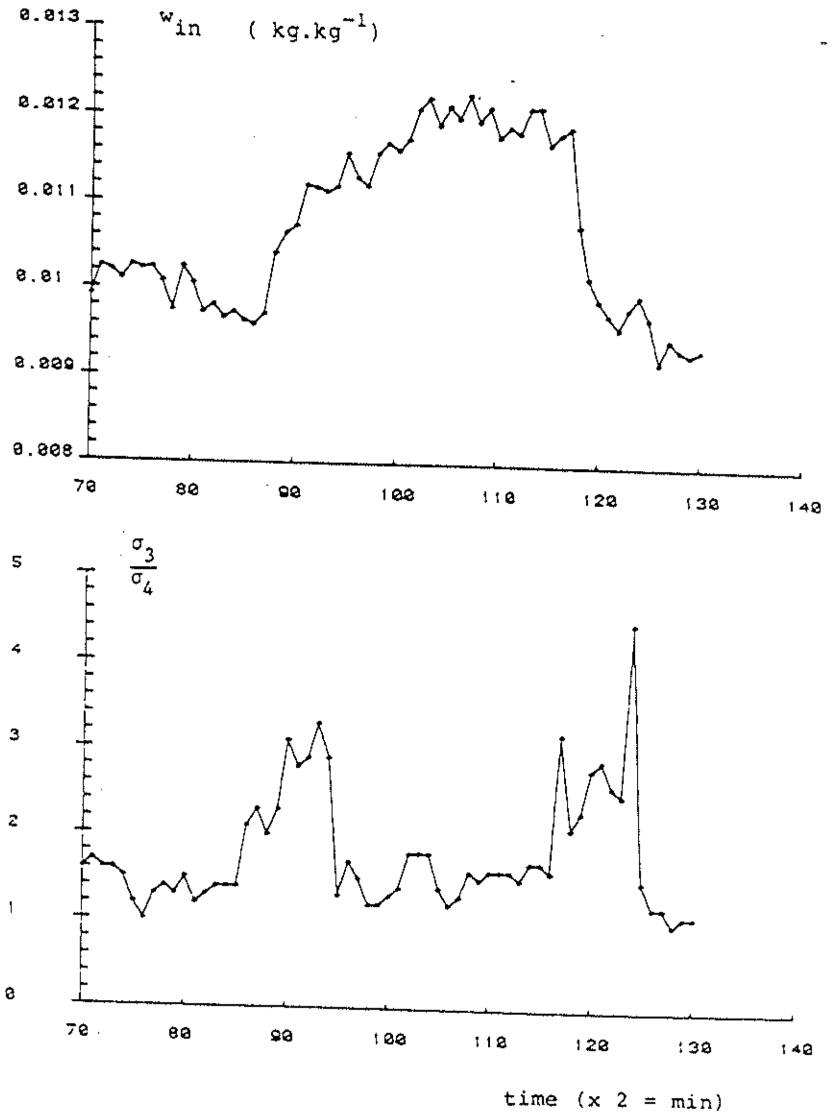
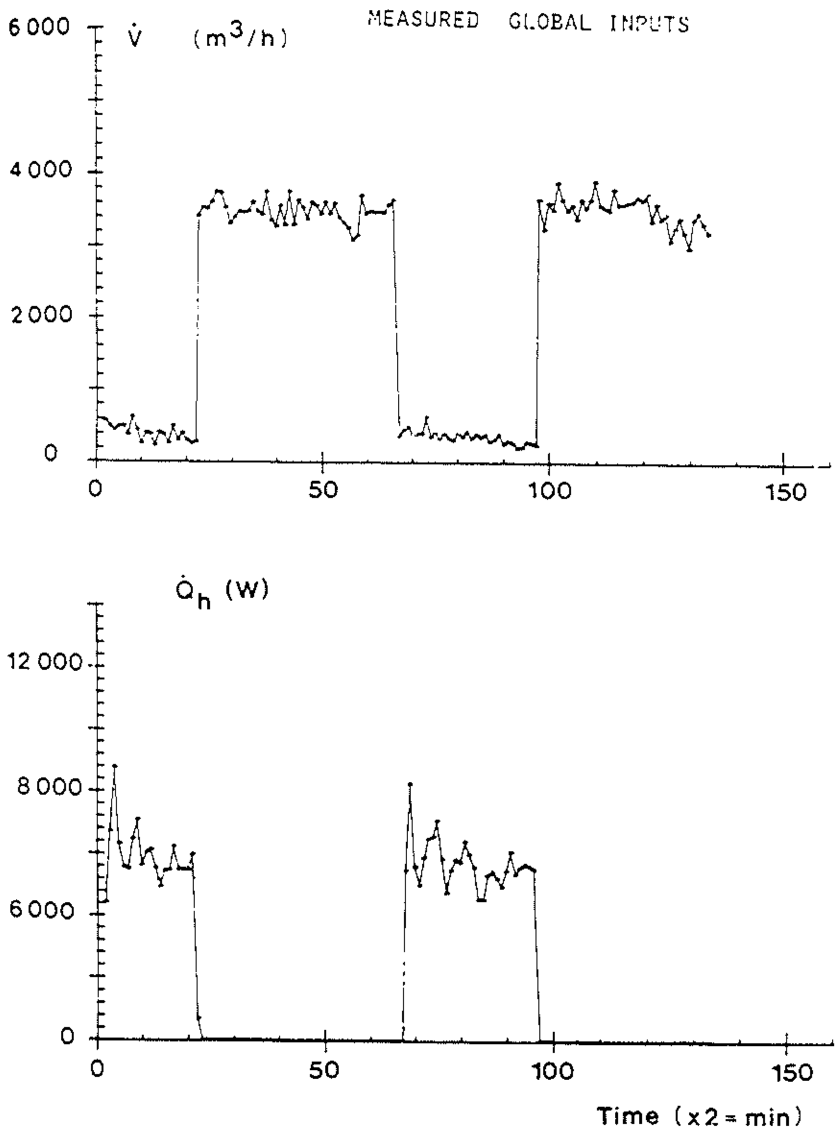


Figure 4 : $\frac{\sigma_3}{\sigma_4}$ as a measure for the signal dynamics to noise ratio.



Figur . Example of measured signal of the global inputs ventilating ...at supply.

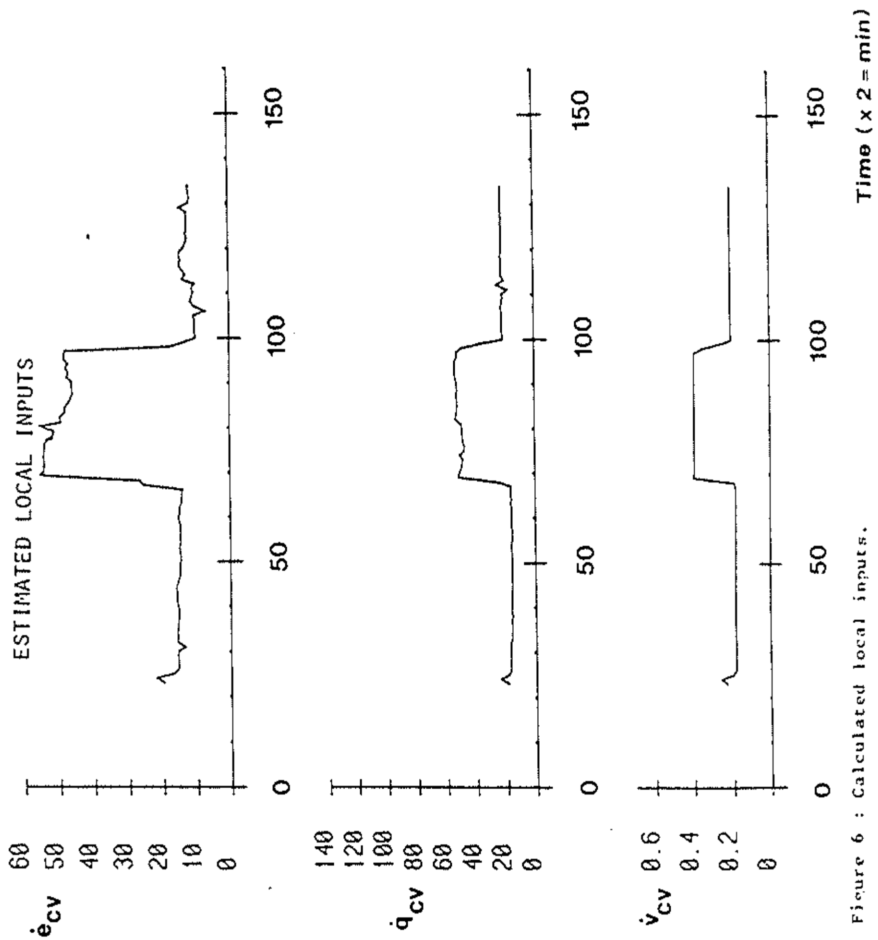


Figure 6 : Calculated local inputs.

MEASURED AND MODELLED OUTPUT

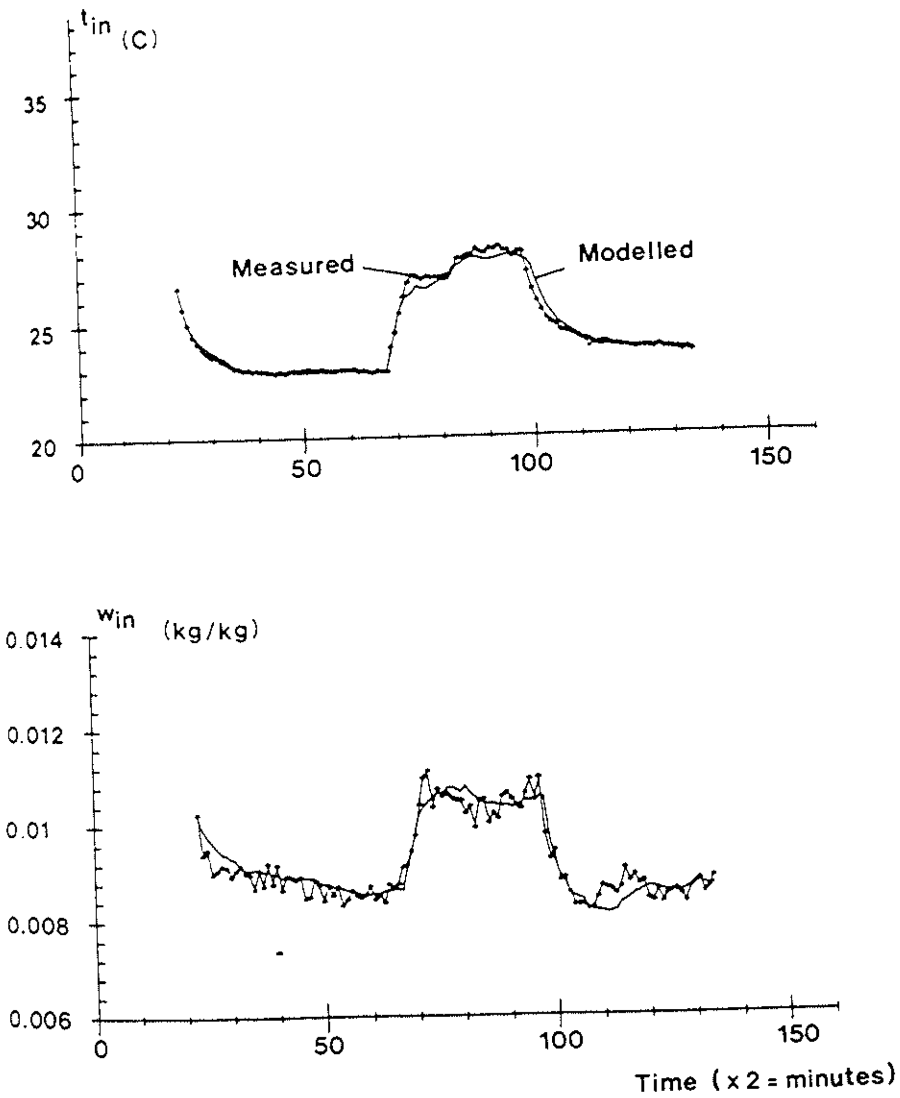


Figure 7 : Measured and modelled output of inside temperature and humidity.

DISCUSSION

DEXTER A.L. (U.K.)

What are the advantages of your identification procedure over more conventional least squared methods of estimating the parameters of a linear difference equation which relates the humidity and temperature to the global inputs of the system ?

ANSWER :

The model concept consists of defining a control volume around each temperature and humidity sensor. Inputs to this control volume are local fresh air flow, local humidity flow and local heat flow. The identification proceeds in two stages. First, the local input sequences are identified for different regimes of the global inputs. Secondly, the non linear relations between local and global inputs are determined with curve fitting techniques. The advantages of this approach are :

- the results are undoubtful and are interpretable in a physically meaningful way. The behaviour of temperature and humidity is explained by the local inputs to the control volume.
- the nonlinear relationship between global and local inputs allows to study the air flow pattern in the non-perfectly mixed airspace (see reference 18). Clearly, these advantages are not met by a linear difference equation fitting the data since this will only lead to imposing a mathematical framework without any need to interprete the results as physically meaningful quantities.

PEDERSEN C.O. (U.S.A.)

1. What is the advantage of this particular model over some other 3-parameters models ?
2. Can the model be used a priori for modelling, not only in an on-line identification scheme ?

ANSWER :

1. See answer to the question of M. Dexter.
2. In order to calculate the nonlinear relations between local and global inputs, several regimes of the global inputs are needed. Hence, some kind of on-line control of the inputs is necessary in order to excite the optimal global inputs. This means that the model can be used for off-line simulations but only if relationships between local inputs and global inputs have been determined in a preceding identification.

PARENT P. (France)

1. How can you prove that your parameter estimation is good on a statistical point of view when you are dealing with a short sample of data (4 to 6) ?
2. When you are making transition on two inputs at the same time, how can you prove that estimated coefficients are not biased by correlated inputs ?

ANSWER :

1. The number of data used for each identification step in the procedure is limited and indeed is very important. The reliability of the parameter estimation depends on the choice of the number of rows in the data matrix used in the singular value decomposition. If this number is too small, then the noise has too much influence on the identified parameters and they behave very wildly. This can be easily detected by calculating their standard deviation. If however this number of rows is too high, then every short time dynamic action is smoothed out and the dynamic action of the signal is not recognized. Hence it is necessary that the signals show enough "persistant excitation" in order to get reliable estimates. Therefore the number of rows has to be adapted in the procedure and it can be shown that the singular values of the data matrix can be used to measure these conditions (reference 18). Because the number of available data for identification is limited in an on-line procedure that can be used in the process-controller, it is not our intention to claim statistical properties. The results obtained by this SVD-technique prove however that it is possible to become reliable estimations of parameters that have a physical meaning (reference 18).

2. Before making transition on two inputs at the same time as shown here as an example, the coefficients have been estimated for separated steps on the inputs. Those steps were produced for different combinations of the regimes of the separated global inputs. Afterwards, it was controlled whether the same parameters were estimated while using transition on two inputs at the same time.

NAHKLE M.

How complex and what is the order of the data matrix on which you are applying the singular value decomposition technique ?

ANSWER :

The matrix that is decomposed by the singular value decomposition is highly structured and has the following form e.g. for humidity :

$$m \times 4 \text{ matrix } (w) = \begin{bmatrix} 1 & w_{out}(0) & w_{in}(0) & w_{in}(1) \\ 1 & w_{out}(1) & w_{in}(1) & w_{in}(2) \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ 1 & w_{out}(m-1) & w_{in}(m-1) & w_{in}(m) \end{bmatrix}$$

An analogous matrix is computed for the temperature as shown in equation (5) in the paper. The choice of the number of rows is a compromise between noise sensitivity and what is commonly called the "persistant excitation" in the identification context. If the number of rows is small, the results are adapted over a small time horizon but the noise can have a lot of influence on the singular value decomposition. If the number of rows is large, the results are "averaged" over a longer time interval but if meanwhile humidity (and temperature) have reached an equilibrium level, the solution of the identification tends to be badly conditioned. The reason is that the input signals are not "excited" enough to ensure the uniqueness of the identified solution. In this application, it was determined experimentally that the optimal choice for the number of rows lies between 6 and 8 to become a good compromise between noise sensitivity and optimal conditioning of the identification problem. Because of this low number of rows and columns the computational complexity of the S.V.D. is negligible.

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If the reference volume was varying on time, then the equations (1) would have to be reformulated in order to keep their physical meaning (energy and moisture conservation).

ANSWER :

To prevent from such a reformulation, the local inputs of the control volume are expressed in the appropriate units PER UNIT OF VOLUME. For this reason we use the volumetric concentration of fresh air flow rate, volumetric concentration of heat flow and moisture flow instead of the fresh air flow rate, heat flow and moisture flow. Hence, the real magnitude of the control volume is not significant anymore.