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MODEL PREDICTIVE CONTROL OF THE AIR FLOW PATTERN AND THE RESULTING TEMPERATURE DISTRIBUTION IN AN IMPERFECTLY MIXED VENTILATED AIR SPACE

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ABSTRACT

In ventilated spaces such as offices, museums, industrial workplaces, greenhouses, livestock buildings,... important 3-D gradients of temperature often occur which are due to an imperfect mixing of the air in the ventilated space. A laboratory test installation was built to analyse the process of imperfect mixing in more detail and under controlled conditions. In the test installation the ventilation rate can be varied between 80 and 300 m3/h. Different air flow patterns can be generated using the ventilation rate as control input. Five heating elements are positioned at the bottom of the test room to simulate the heat production of the occupants (man, animal, plant, product). In order to measure the 3-D temperature distribution, 36 temperature sensors are positioned in a 3-D grid.

A 'grey box model' was developed to predict the dynamic response of temperature in the 'well mixed zone' around a local sensor to non-linear variations of the ventilation rate as control input. The 'grey box model' provides physical insight in the process of fresh air and heat transport towards the 'well mixed zone'. The model can be used as a basis for control purposes. To show this, a Model Predictive Control or MPC algorithm has been developed based on the 'grey box model' and has been implemented in the test room. The implemented MPC algorithm has been used to control the temperature in the 'well mixed zone' around the sensor according to a predefined reference trajectory. A total amount of 10 control experiments was performed to test the accuracy of the MPC algorithm. From the 10 control experiments the mean standard error (mse) between the realised and predefined temperature trajectory was found to be 0.2°C on average.

Keywords: Model Predictive Control, Model, Temperature, Air Flow Pattern

INTRODUCTION

In civil engineering, agriculture and industry the ventilation rate is often used to control the indoor environment (temperature, moisture content, air velocity, gas and dust concentration,...). An adequate control of the indoor environment is required to optimise the production process or to improve welfare and health (Fanger, 1970; Monteith and Mount , 1973; Mount, 1979). Up to now, the indoor environment in a greenhouse or livestock building is mostly considered to be uniform. However, measurements in various application areas (office, museum, industrial workplace, greenhouse, livestock building,...) indicate that important 3-D gradients of environmental variables often occur, which are due to an imperfect mixing of the air in the ventilated space (Berckmans D., 1986). In these cases of imperfect mixing the 3-D gradients must be taken into account in order to realise a better climate control.

TEST INSTALLATION

In the laboratory a test installation was built to analyse the process of imperfect mixing in more detail and under controlled conditions (Berckmans et al., 1992 (a)). The test room is shown in figure 1. In the test installation [3×2×1.5m] with a volume of 9 m3 the ventilation rate can be varied between 80 and 300 m3/h, resulting in rather high air exchange rates (8.9 - 33.3 refreshments each hour). Different air flow patterns can be generated in the test installation using the ventilation rate as control input. These air flow patterns can be visualised by smoke experiments and quantified by image analysis techniques (De Moor and Berckmans , 1993). Five heating elements at low temperature are positioned at the bottom of the test room to simulate the heat production of the occupants (man, animal, plant, product). In order to measure the 3-D distribution of temperature in the test room, 36 temperature sensors are positioned in a 3-D grid as shown in figure 1. From many experiments it was found that the temperature in the test room is far from homogeneous and that 3-D gradients up to 4 °C often occur. Moreover, it was found that the 3-D distribution of temperature can be related to the air flow pattern in the test room (De Moor and Berckmans, 1993).

'GREY BOX MODEL'

In order to realise an efficient model based control of the temperature distribution in the ventilated air space, modern control theory can be applied. Therefore, it is first required to have a dynamic mathematical model of the process of fresh air an heat transport in the ventilated space. An adequate dynamic model was developed for this reason.

Model structure

Measurements indicate that the air in the test room is not perfectly mixed. Although there is not a perfect mixing, it is always possible to define a 'well mixed zone' around a local sensor, in which there is a better mixing and consequently an acceptable gradient of temperature. A model was developed to predict the dynamic response of temperature Ti [°C] in the defined 'well mixed zone' to non-linear variations of the ventilation rate V [m3/h] as control input (Berckmans, 1986). The block diagram of the model is represented in figure 2 and explained in more detail in previous publications (Berckmans, 1986; Berckmans et al., 1992 (b)). The model can be considered as a 'grey box model' consisting of a 'black box part' and a 'white box part':

1. The 'black box part' consists of the relationship between the ventilation rate V [m3/h] through the test room and the volumetric concentrations of fresh air flow rate v_c [m3/s.m3] and of heat flow q_c [J/s.m3] entering the defined 'well mixed zone'. This relationship is not presented under the form of physical equations, but estimated using a mathematical identification procedure (De Moor and Berckmans, 1994; De Moor and Berckmans, 1996). The first model part can therefore be considered as the 'black box part' of the 'grey box model'. In previous publications it has been shown that this model part can be related to the different air flow patterns (falling, unstable and horizontal) in the test room (De Moor, 1996; Janssens et al., 1996).
2. The second part of the 'grey box model' consists of the physical relationship between the temperature Ti [°C] in the defined 'well mixed zone' and the volumetric concentrations of fresh air flow rate v_c [m3/s.m3] and of heat flow q_c [J/s.m3] entering the 'well mixed zone'. Since this model part is based on the physical laws of energy and mass conservation, it forms the 'white box part' of the 'grey box model'.

Instead of the 'grey box model', a 'black box model' could also be developed. Such a model is less complicated and easier to implement in a controller, but does not provide any physical insight in the process of fresh air and heat transport in the ventilated space. Since one of the main motivations beside control was to get more physical insight in this process, a 'grey box model' was preferred above a 'black box model' (De Moor and Berckmans, 1994).

'Grey box model' for the 36 sensor positions

A total amount of 50 step up experiments was performed in the test room to identify the 'grey box model' for the 36 sensor positions (De Moor M. and Berckmans D., 1994). The 36 identified 'grey box models' have the same 'white box part', but a different 'black box part' (De Moor M., 1996). The 'black box parts' are different, since fresh air and heat are not equally distributed in the test room.

Validation of the 36 'grey box models'

Four validation experiments were performed in the test room to validate the 36 'grey box models'. In these experiments the ventilation rate V [m3/h] was varied randomly between 80 and 300 m3/h. The temperature Ti [°C] was measured each second at the 36 sensor positions and compared to the predicted values. The average mean standard error (mse_{av}) was used to validate the temperature predictions of the 36 'grey box models'. The average mean standard error (mse_{av}) is defined in the equations (1) and (2), in which $Ti_{pred}(i,j)$ and $Ti_{meas}(i,j)$ are the predicted and measured temperature at sensor position i and at time step j, and in which n is the total number of time steps in the validation experiment.

$$mse_{av} = \frac{\sum_{i=1}^{36} mse(i)}{36} \qquad (1)$$

in which $mse(i) = \dfrac{\sum_{j=1}^{n} \sqrt{(Ti_{pred}(i,j) - Ti_{meas}(i,j))^2}}{n}$ (2)

One of the validation experiments is shown in the figures 3.1 and 3.2. In table 1 an overview is given of the four validation experiments and the calculated average accuracy (mse_{av}) of the 36 'grey box models'. From this table, it can be concluded that the dynamic response of temperature at a sensor position resulting from non-linear variations of the ventilation rate can be predicted with an average accuracy (mse_{av}) of 0.33 C.

MODEL PREDICTIVE CONTROL

It is clear that the temperature cannot be controlled at the 36 sensor positions at the same time with the ventilation rate as the only control input. The temperature can only be controlled at one position. That is not a real problem for a later use in practise, since there it is only important to control the temperature in the near micro-environment around the occupants (man, animal, plant, product).

In this section it is explained that the identified 'grey box model' for a certain sensor position can be used for a local temperature control. This will be illustrated for sensor position [521]. The position of this sensor is shown in figure 1.

Taking into account the different advantages claimed in literature (Clarke, 1988; Garcia et al., 1989) a Model Predictive Control algorithm or MPC algorithm has been developed based on the 'grey box model' for sensor position [521] and has been implemented in the test room. The objective of this implemented MPC algorithm is to control continuously the temperature in the 'well mixed zone' around sensor [521] with the aim to follow a predefined temperature trajectory. In the MPC algorithm the identified 'grey box model' for sensor position [521] is used to predict the dynamic response of temperature at that position to future actions of the ventilation rate as the control input. By minimising the mean standard error (mse) between the predicted output of the 'grey box model' and the predefined reference temperature trajectory the future actions of the ventilation rate as control input can be calculated. The theoretical background of the control algorithm is described in more detail in literature (Clarke et al., 1987; Taylor et al., 1994).

The MPC algorithm as described above was programmed in the software packet MATLAB and implemented in the test room. A total amount of 10 control experiments was performed in the test installation to evaluate the accuracy of the MPC algorithm. In the figures 4.1 and 4.2 an example is given of such a control experiment. In figure 4.1 the realised temperature at sensor position [521] is compared to the predefined reference temperature trajectory. The computed input sequence of the ventilation rate which has been applied to the real system in order to achieve the desired reference trajectory is shown in figure 4.2. From figure 4.1 it can clearly be seen that the MPC algorithm can be used to control the temperature at the considered sensor position. The small variations of temperature around the predefined reference trajectory can mainly be assigned to turbulences and measurement noise which are not taken into account in the 'grey box model'.

From the 10 performed control experiments in the test installation the mean standard error (mse) between the realised and predefined temperature trajectory was calculated as a measure for the accuracy of the implemented control algorithm. This value was found to be 0.2 °C on average.

CONCLUSIONS

A 'grey box model' was developed to predict the dynamic response of temperature in the 'well mixed zone' around a sensor to non-linear variations of the ventilation rate as control input. Based on this 'grey box model' a Model Predictive Control or MPC algorithm has been developed and implemented in the test room in order to control the temperature around the sensor according to a predefined reference trajectory. From a total amount of 10 performed control experiments in the test room the mean standard error (mse) between the realised and predefined temperature trajectory was found to be 0.2°C on average.

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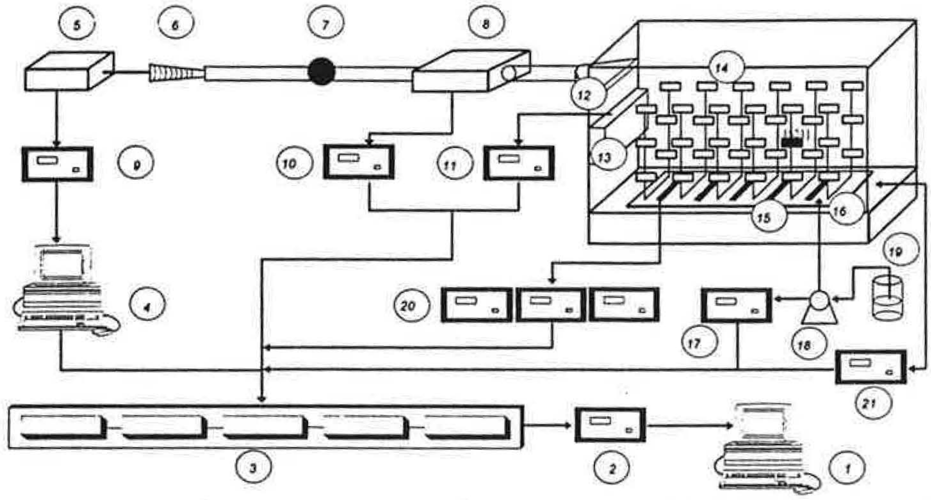
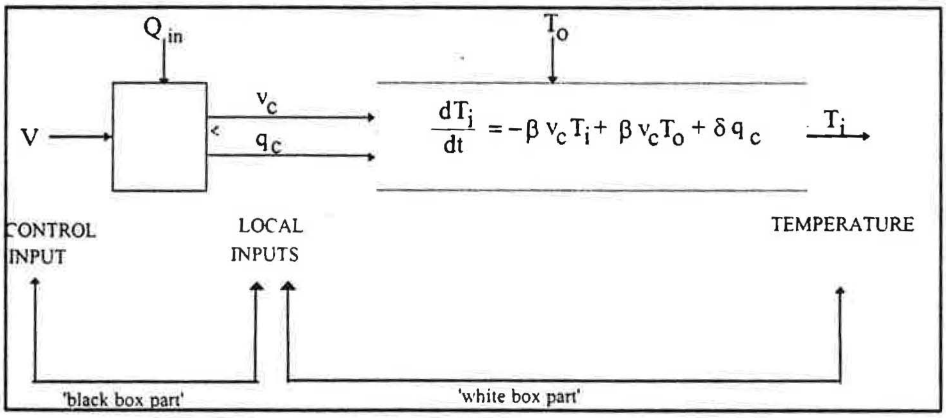


1. Minicomputer (monitor, floppy disc, to store and visualise the measured data). **2.** Parallel-interface for digital and analogue signals. **3.** Scan- and measurement unit. **4.** Minicomputer (to control and measure the produced air flow rate). **5.** Stepmotor to control the position of the cone, used as diaphragm. **6.** Cone, used as diaphragm, to produce the desired air flow rate. **7.** Centrifugal fan, to generate a ventilating rate. **8.** Cooling installation to control the inlet temperature. **9.** Differential pressure transducer to measure pressure difference between the test chamber and the envelope. **10.** Control- and measurement unit of the cooling installation. **11.** Control- and measurement unit of the heating element. **12.** Air inlet (slot inlet). **13.** Heating element (not used). **14.** Three dimensional grid of 36 temperature sensors. **15.** Aluminium semi conductor heat sinks to provide internal heat production. **16.** Undeep water reservoir with a streamer containing hot water to generate the internal moisture production (not used). **17.** Unit to control and measure the amount of water supplied to the undeep water reservoir. **18.** Water pump. **19.** Water supply reservoir. **20.** Power supplies for internal heat production. **21.** Pressure difference measurement used to control the outlet fan.

Figure 1: Test installation.



Q_{in}	: heat production in the test room [J/s]
V	: ventilation rate through the test room [m3/h]
v_c	: volumetric concentration of fresh air flow rate entering the 'well mixed zone' [m3/s.m3]
q_c	: volumetric concentration of heat flow entering the 'well mixed zone' [J/s.m3]
T_i	: temperature in the 'well mixed zone' [°C]
T_o	: temperature of the incoming air in the test room [°C]
t	: time [s]
,	: physical constants

Figure 2: Block diagram of the 'grey box model'

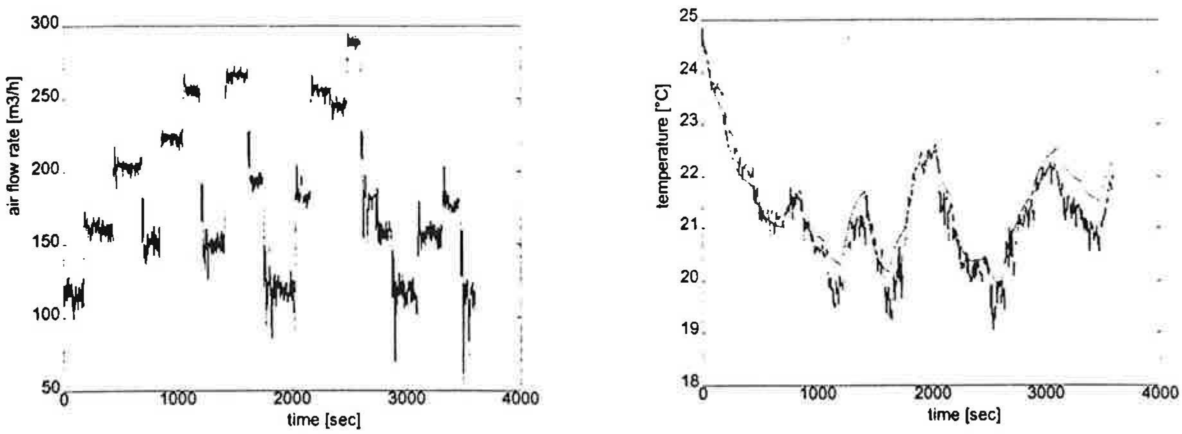


Figure 3: (1) Non-linear variations of the ventilation rate during a validation experiment. (2) The predicted temperature compared to the measured temperature at sensor position [521]. The mse is 0.34 C. The position of sensor [521] is shown in figure 1.

experiment number	mse_{av} [°C]
experiment 1	0.31
experiment 2	0.30
experiment 3	0.37
experiment 4	0.36
mean	**0.33**

Table 1: The calculated average accuracy (mse_{av}) of the 36 'grey box models'.

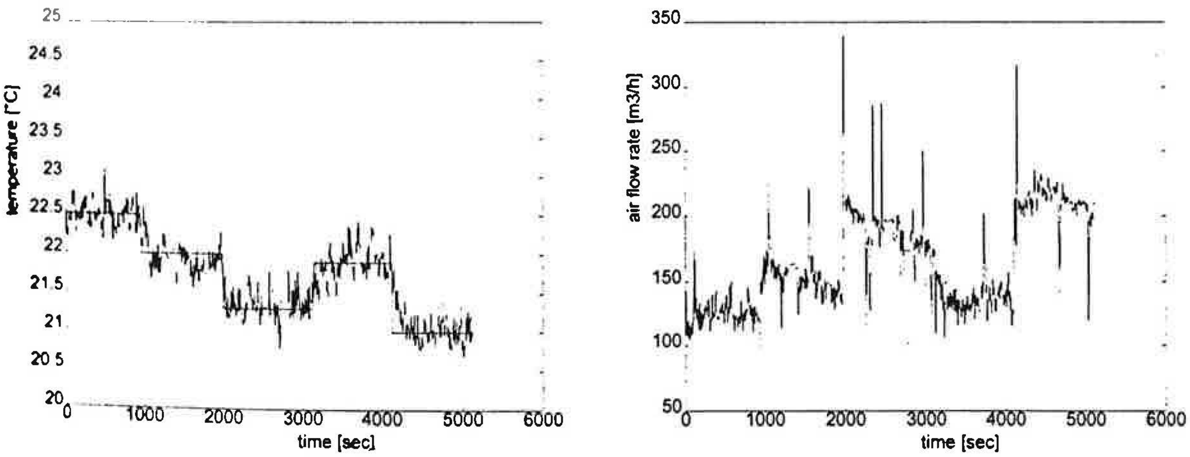


Figure 4: (1) The realised temperature in the 'well mixed zone' around sensor [521] compared to the predefined reference temperature trajectory. (2) The realised ventilation rate in the test room to achieve the desired reference temperature trajectory.