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VALIDATION OF A MODEL CONCEPT TO MODEL THE 3-D DISTRIBUTION OF TEMPERATURE AND HUMIDITY IN AN IMPERFECTLY MIXED VENTILATED AIR SPACE

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Abstract

In a ventilated test room with a high air exchange rate (8.9 - 33.3 refreshments each hour) a model was developed and identified to model the dynamic response of the 3-D distribution of temperature and absolute humidity to non-linear variations of the ventilation rate as control input. The model consists of two parts The first part is the relationship between the ventilation rate and the 3-D distribution of fresh air, heat and moisture in the test room. The second part is the relationship between this 3-D distribution of fresh air, heat and moisture and the 3-D distribution of temperature and absolute humidity in the test room.

In this paper it is shown that:

1. the first model part can be related to the different air flow patterns in the test room. This confirms the hypothesis of the model that the air flow pattern is the main carrier of fresh air, heat and moisture to the different positions in the test installation.
2. the dynamic response of the 3-D distribution of temperature and humidity in the test room resulting from non-linear variations of the ventilation rate can be predicted with an average accuracy (mse_{av}) of 0.33 °C and 0.57 $g_{water}/kg_{dry\ air}$.

1. 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,...) in a ventilated air space. An adequate control of the indoor environment in a ventilated space is required to optimise the production process or to improve welfare and health (Fanger P.O., 1970; Monteith J.L. and Mount L.E., 1973; Mount L.E., 1979). Up to now, the indoor environment in a ventilated space is mostly considered to be uniform. However, measurements in various application areas (office, transport system, museum, industrial hall, livestock building, greenhouse, storage place...) 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.

1.1. 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 D. et al., 1992). The test installation 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 M. and Berckmans D., 1993). A hot water basin and 5 heating elements at low temperature are positioned at the bottom of the test room to simulate the moisture and heat production of the living organism (man, animal, plant) or product. In order to measure the 3-D distribution of temperature and humidity in the test room, 24 positions are provided with a temperature and a humidity sensor as shown in figure 2. From 16 experiments it was found that the 3-D distribution of temperature and humidity can be related to the air flow pattern in the test room (De Moor M. and Berckmans D., 1993).

1.2. 'Grey box model'

Although the air in the test installation is not perfectly mixed, it is always possible to define a **'well mixed zone'** around a certain sensor, in which there is a better mixing which results in an acceptable gradient of temperature and humidity. In the laboratory a model has been developed to model the dynamic response of temperature Ti [°C] and absolute humidity Xi [$kg_{water}/kg_{dry\ air}$] in the defined 'well mixed zone' to non-linear variations of the ventilation rate V [m3/h] as control input (Berckmans D., 1986). In the model two hypotheses are taken into account:

1. Since the air exchange rate in the test installation is rather high, the air flow pattern is considered to be the main carrier of fresh air (from the air inlet), heat (from the 5 heating elements and the walls) and moisture (from the hot water basin) towards the defined 'well mixed zone'.
2. These amounts of fresh air, heat and moisture entering the 'well mixed zone' determine the resulting temperature and absolute humidity in the 'well mixed zone'.

The model (concept, block diagram) is represented in figure 3 and explained in more detail in previous publications (Berckmans D., 1986; Berckmans D. et al., 1992). The model can be considered as a 'grey box model' consisting of two parts:

1. The first part consists of the relationships between on the one hand the ventilation rate V [m3/h] through the test room and on the other hand the volumetric concentrations of fresh air flow rate v_c [m3/s.m3], of heat flow q_c [J/s.m3] and of moisture flow c_c [kg_{water}/s.m3] entering the defined 'well mixed zone'. These v_c/V-, q_c/V- and c_c/V-relationships for the defined 'well mixed zone' are not presented under the form of physical laws, but estimated using a mathematical identification procedure (De Moor M. and Berckmans D., 1994; De Moor M. and Berckmans D., 1996). The first

model part can therefore be considered as the 'black box part' of the 'grey box model'. According to the first hypothesis of the model, the estimated v_c/V-, q_c/V- and c_c/V-relationships can be expected to be a measure for the air flow pattern in the test room.

2. The second part of the 'grey box model' consists of the physical relationship between on the one hand the temperature Ti [°C] and the absolute humidity Xi [$kg_{water}/kg_{dry\ air}$] in the defined 'well mixed zone' and on the other hand the volumetric concentrations of fresh air flow rate v_c [m3/s.m3], of heat flow q_c [J/s.m3] and of moisture flow c_c [kg_{water}/s.m3] entering this 'well mixed zone'. Since this second model part is based on the physical laws of energy and mass conservation, it forms the 'white box part' of the 'grey box model'.

As described in previous publications (Berckmans D., 1986; De Moor M. and Berckmans D., 1994) a 'grey box model' has been developed for two reasons:

1. To be used for a model based predictive control of temperature and absolute humidity in a 'well mixed zone' using the ventilation rate as control input. For this purpose a 'black box model' could also be developed.
2. To provide a better physical insight in the process of fresh air, heat and moisture transport in an imperfectly mixed ventilated air space with a rather high air exchange rate. This is the main reason why a 'grey box model' has been preferred above a 'black box model'.

1.3. SIMO model

Based on 50 step up experiments (De Moor M. and Berckmans D., 1994) a 'grey box model' has been identified for the 24 sensor positions in the test installation. These 24 'grey box models' have the same 'white box part', but different v_c/V-, q_c/V- and c_c/V-relationships as 'black box part' (De Moor M., 1996). The 24 'grey box models' together form the Single Input Multi Output or SIMO model for the test room. The block diagram of the SIMO model (1 input, 48 outputs) is represented in figure 4. Just as its 24 components, the SIMO model consists of a 'black box part' and a 'white box part':

1. The 'black box part' is the relationship between the ventilation rate and the 3-D distribution of fresh air, heat and moisture in the test room. This part consists of the 24 identified v_c/V-, q_c/V- and c_c/V-relationships which are all different.
2. The 'white box part' is the relationship between the 3-D distribution of fresh air, heat and moisture and the resulting 3-D distribution of temperature and absolute humidity in the test room.

2. Objectives

The main objectives of this paper are:

1. To test whether the 24 identified v_c/V-, q_c/V- and c_c/V-relationships contained in the 'black box part' of the SIMO model can be related to the different air flow patterns in the test installation. In that case the air flow pattern can be considered as the main carrier of fresh air (from the air inlet), heat (from the 5 heating elements and the walls) and moisture (from the hot water basin) towards the different positions in the test room.
2. To show that the SIMO model can be used to predict the dynamic response of the 3-D distribution of temperature and humidity to non-linear variations of the ventilation rate as control input.

3. The 24 identified v_c/V-, q_c/V- and c_c/V-relationships of the SIMO model in relation to the different air flow patterns in the test installation

According to the first hypothesis of the model, the identified v_c/V-, q_c/V- and c_c/V-relationships for the 24 sensor positions in the test installation can be expected to be a measure for the air flow pattern. To test this hypothesis, the air flow pattern in the ventilated test room was first visualised and quantified for different values of the ventilation rate (De Moor M. and Berckmans D., 1993). In figure 5 the centreline of the air flow pattern is visualised for ventilation rates of 122, 158, 249 and 298 m3/h. In general 3

categories of air flow patterns can be distinguished in the test installation: a horizontal air flow pattern (V>260 m3/h), an unstable air flow pattern (240 m3/h<V<260 m3/h) and a falling air flow pattern (V<240 m3/h).
It can now be shown that the identified v_c/V-, q_c/V- and c_c/V-relationships for the 24 sensor positions can be related to these 3 different categories of air flow patterns. As an example, the estimated v_c/V-, q_c/V- and c_c/V-relationships for sensor position [421] are presented in the figures 6.1, 6.2 and 6.3 and related to the 3 different categories of air flow patterns as shown in the paragraphs 3.1, 3.2 and 3.3. As explained in previous publications (De Moor M. and Berckmans D., 1994; De Moor M. and Berckmans D., 1996) these relationships were identified based on 50 step up experiments. The position of sensor [421] can be found in the figures 1, 2 and 5. The exact position of the sensor is at a horizontal distance of 155 cm from the air inlet and at a vertical height of 160 cm.

3.1. v_c/V-relationship for sensor position [421] (figure 6.1)

In the v_c/V-relationship for sensor position [421], three different areas can be distinguished:
1. V<240 m3/h: since there is a falling air flow pattern, not much of the incoming fresh air is passing through the 'well mixed zone' around sensor [421]. This results in small v_c-values.
2. V>260 m3/h: since the air flow pattern is horizontal, most of the incoming fresh air is passing through the 'well mixed zone' around the sensor. This results in larger v_c-values.
3. 240 m3/h<V<260m3/h: since the air flow pattern is unstable, small and larger amounts of fresh air can pass through the considered 'well mixed zone'.

It can be concluded from the figure that the v_c/V-relationship for sensor position [421] can be related to the 3 categories of air flow patterns in the test installation. This confirms the hypothesis that the air flow pattern is the main carrier of fresh air from the air inlet towards the considered 'well mixed zone'.

3.2. q_c/V-relationship for sensor position [421] (figure 6.2)

The q_c/V-relationship for sensor position [421] can also be related to the 3 different categories of air flow patterns in the test installation. This confirms the hypothesis that the air flow pattern is the main carrier of heat from the 5 heating elements and the walls towards the 'well mixed zone' around the sensor.

3.3. c_c/V-relationship for sensor position [421] (figure 6.3)

The c_c/V-relationship for sensor position [421] can also be linked to the 3 categories of air flow patterns in the test room. This confirms the hypothesis that the air flow pattern is the main carrier of moisture from the hot water basin to the considered 'well mixed zone'.

It can also be demonstrated that the v_c/V-, q_c/V- and c_c/V-relationships for the other sensor positions can be related to the different air flow patterns in the test installation (De Moor M., 1996). This confirms the hypothesis that the air flow pattern is the main carrier of fresh air (from the air inlet), heat (from the 5 heating elements and the walls) and moisture (from the hot water basin) towards the different sensor positions in the test room. This is also the reason why the 3-D distribution of temperature and humidity can be related to the air flow pattern in the test installation (De Moor M. and Berckmans D., 1993).

4. Validation of the SIMO model

To check whether the identified SIMO model consisting of the 24 'grey box models' can be used to predict the dynamic response of the 3-D distribution of temperature and humidity to non-linear variations of the ventilation rate as control input, four validation experiments were performed in the test room. In these experiments the ventilation rate V [m3/h] was varied randomly between 80 and 300 m3/h. The temperature Ti [°C] and the absolute humidity Xi [$kg_{water}/kg_{dry\ air}$] were measured each second at the 24 sensor positions and compared to the predicted values. The average mean standard error (mse_{av}) has been used to validate the Ti and Xi predictions of the SIMO model. The average mean standard error (mse_{av}) is defined in the equations (1) and (2), in which $y_{pred}(i,j)$ and $y_{meas}(i,j)$ are the predicted and measured output variable (Ti or Xi) at sensor position i and at time step j, and in which n is the total number of time steps in the validation experiment.

$$mse_{av} = \frac{\sum_{i=1}^{24} mse(i)}{24} \quad (1)$$

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

One of the validation experiments is shown in the figures 7.1, 7.2 and 7.3. In table 1 an overview is given of the four validation experiments and the calculated average accuracy (mse_{av}) of the SIMO model for the prediction of temperature and humidity. From this table, it can be concluded that the dynamic response of the 3-D distribution of temperature and humidity to non-linear variations of the ventilation rate can be predicted with an average accuracy (mse_{av}) of 0.33 °C and 0.57 $g_{water}/kg_{dry\ air}$.

temp. file	**mse_{av} [°C]**	**hum.file**	**mse_{av} [$g_{water}/kg_{dry\ air}$]**
me0709ta	0.31	me0709va	0.71
me0709tb	0.30	me0709vb	0.53
me0709tc	0.37	me0709vc	0.40
me0709td	0.36	me0709vd	0.65
mean	**0.33**	mean	**0.57**

Table 1: The average accuracy (mse_{av}) of the SIMO model.

5. Conclusions

In a test installation with a high air exchange rate (8.9 - 33.3 refreshments each hour) a SIMO model was developed and identified to model the dynamic response of the 3-D distribution of temperature and absolute humidity to non-linear variations of the ventilation rate as control input. The model consists of a 'black box part' and a 'white box part'. The 'black box part' is the relationship between the ventilation rate and the 3-D distribution of fresh air, heat and moisture in the test room. This part consists of the v_c/V-, q_c/V- and c_c/V-relationships for the 24 sensor positions in the test room. The 'white box part' is the relationship between on the one hand the 3-D distribution of fresh air, heat and moisture and on the other hand the 3-D distribution of temperature and absolute humidity in the test room.
In this paper it has been shown that:

1. the 'black box part' of the SIMO model can be related to the different air flow patterns in the test room. This confirms the hypothesis that the air flow pattern is the main carrier of fresh air, heat and moisture towards the different sensor positions in the test installation.
2. the dynamic response of the 3-D distribution of temperature and humidity in the test room resulting from non-linear variations of the ventilation rate can be predicted with an average accuracy (mse_{av}) of 0.33 °C and 0.57 $g_{water}/kg_{dry\ air}$.

6. References

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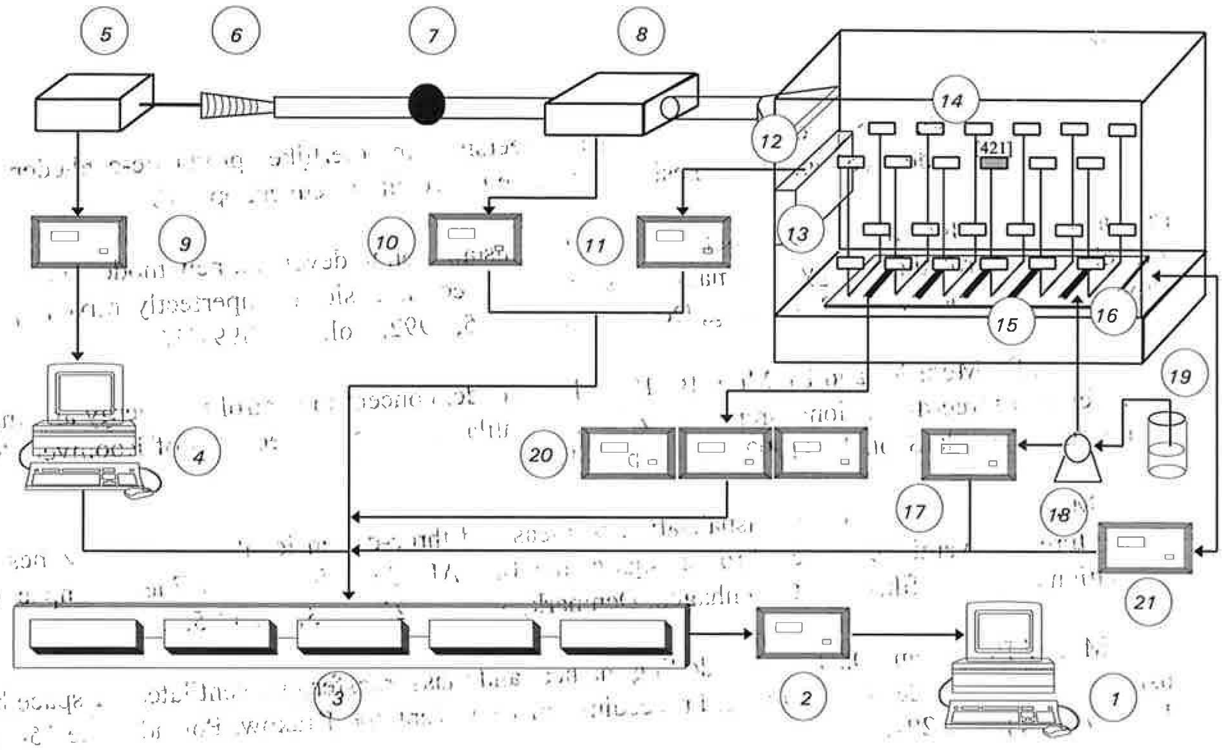


1. Minicomputer (monitor, floppy disc, to store and visualise the measured data). **2.** Parallel-interface for digital and analogue signals. **3.** Scan- and measurement unit. **4.** Minicomputer (to control and measure the produced air flow rate). **5.** Stepmotor to control the position of the cone, 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 temperature and humidity 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. **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.

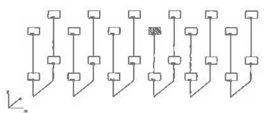
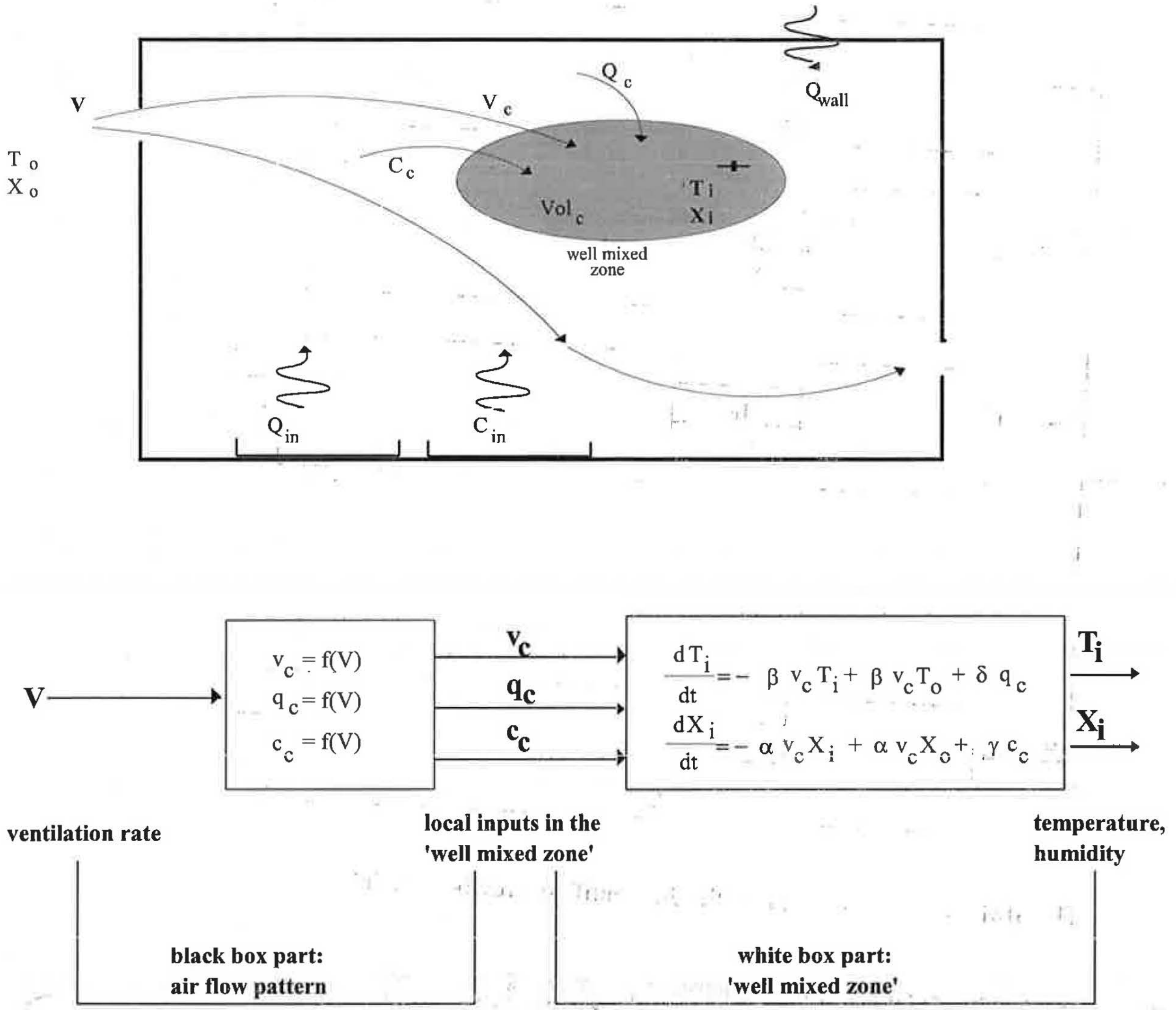


Figure 2: Sensor configuration: 24 positions are provided with a temperature and a humidity sensor.



V : total ventilation rate in the test room [m3/s]
Q_{in} : heat production of the 5 heating elements [J/s]
Q_{wall} : heat exchange with the walls [J/s]
C_{in} : moisture production in the hot water basin [kg_{water}/s]
Vol_c : volume of the 'well mixed zone' [m3]
V_c : part of the total ventilation rate V entering the 'well mixed zone' [m3/s]
Q_c : part of the total heat production $Q_{in}+Q_{wall}$ entering the 'well mixed zone' [J/s]
C_c : part of the total moisture production C_{in} entering the 'well mixed zone' [kg_{water}/s]
v_c :=V_c/Vol_c: volumetric concentration of fresh air flow rate in the 'well mixed zone' [m3/s.m3].
q_c :=Q_c/Vol_c: volumetric concentration of heat flow in the 'well mixed zone' [J/s.m3].
c_c :=C_c/Vol_c: volumetric concentration of moisture flow in the 'well mixed zone' [kg_{water}/s.m3].
T_i : temperature in the 'well mixed zone' [°C]
T_o : outside temperature [°C]
X_i : absolute humidity in the 'well mixed zone' [$kg_{water}/kg_{dry\ air}$]
X_o : outside absolute humidity [$kg_{water}/kg_{dry\ air}$]
t : time [s]
$\alpha,\beta,\gamma,\delta$: combination of physical constants

Figure 3: Concept and block diagram of the model.

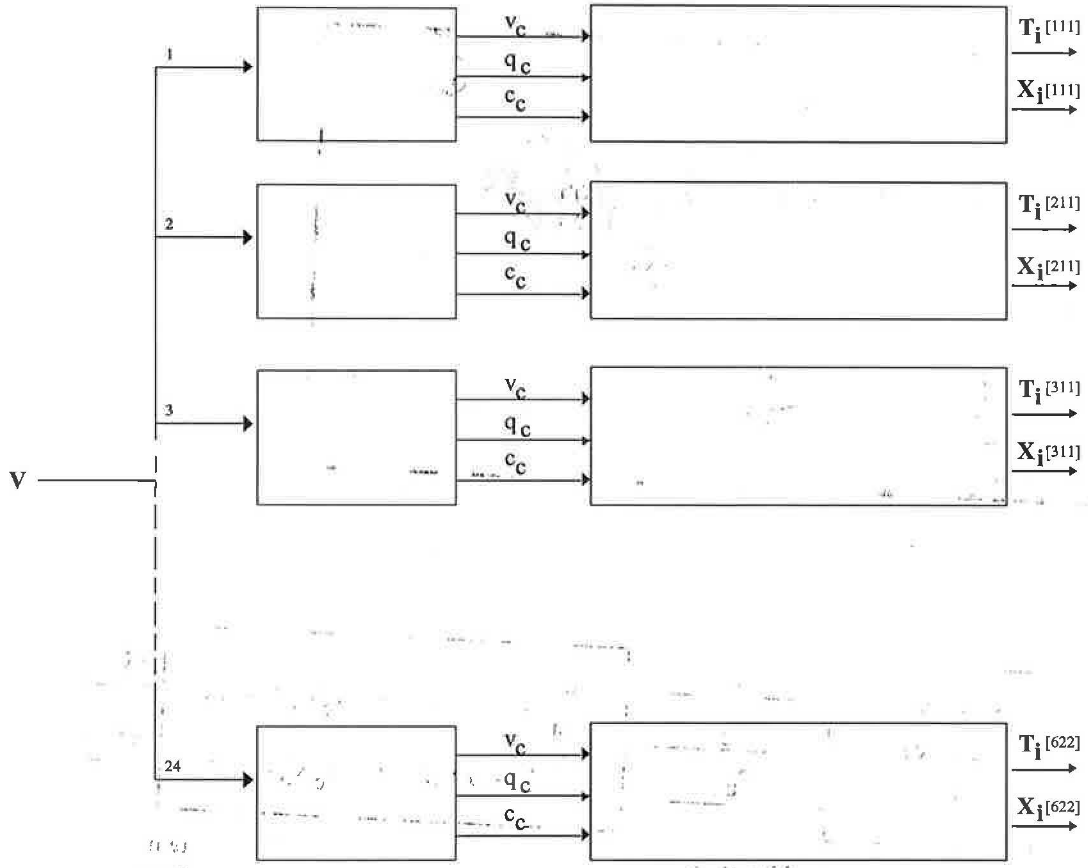


Figure 4: The SIMO model consisting of the 24 identified 'grey box models'.

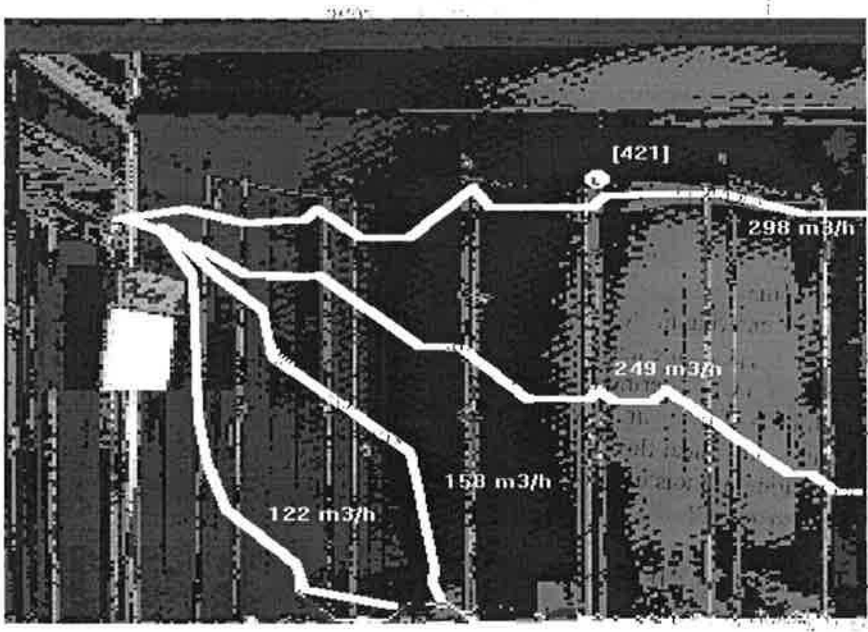


Figure 5: The centreline of the air flow pattern for differnt ventilation rates:
(1) V=122 m3/h: falling air flow pattern
(2) V=158 m3/h: falling air flow pattern
(3) V=249 m3/h: unstable air flow pattern
(4) V=298 m3/h: horizontal air flow pattern

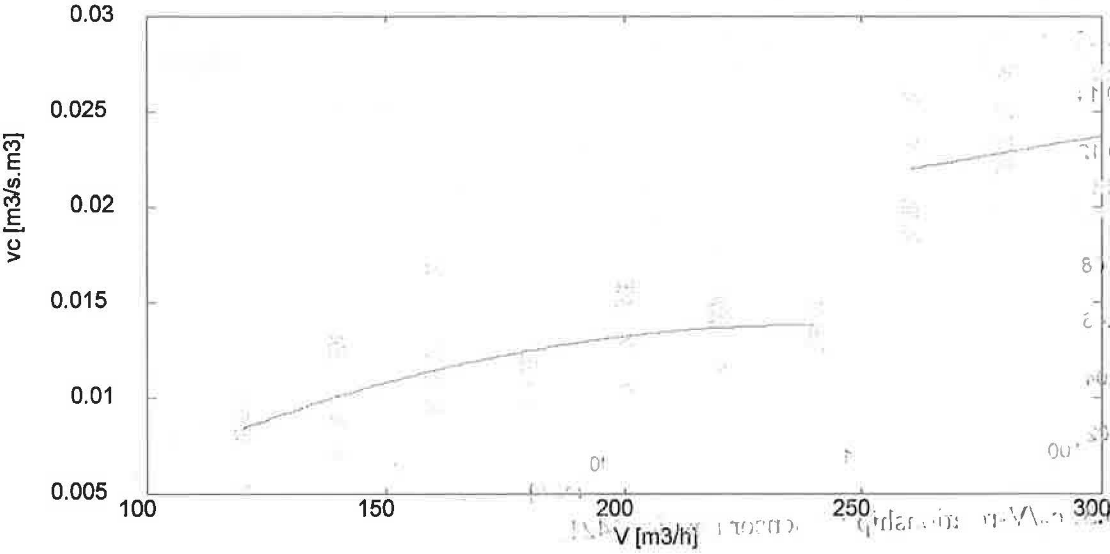


Figure 6.1: v_c/V-relationship for sensor position [421]

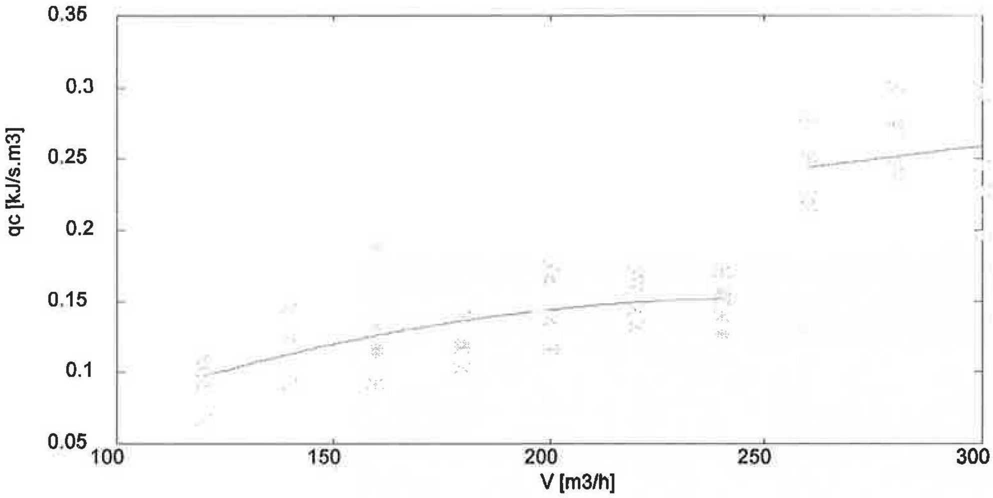


Figure 6.2: q_c/V-relationship for sensor position [421]

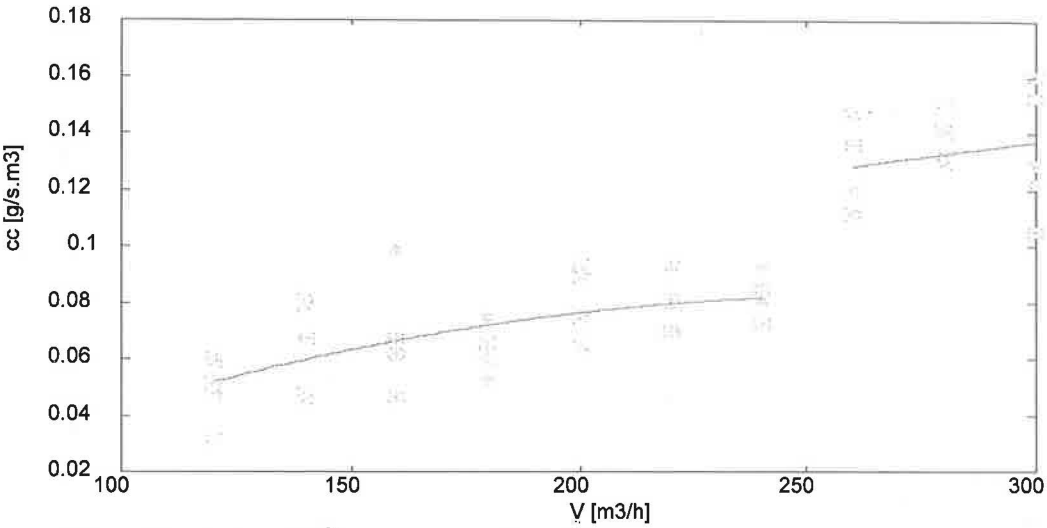


Figure 6.3: c_C/V-relationship for sensor position [421]

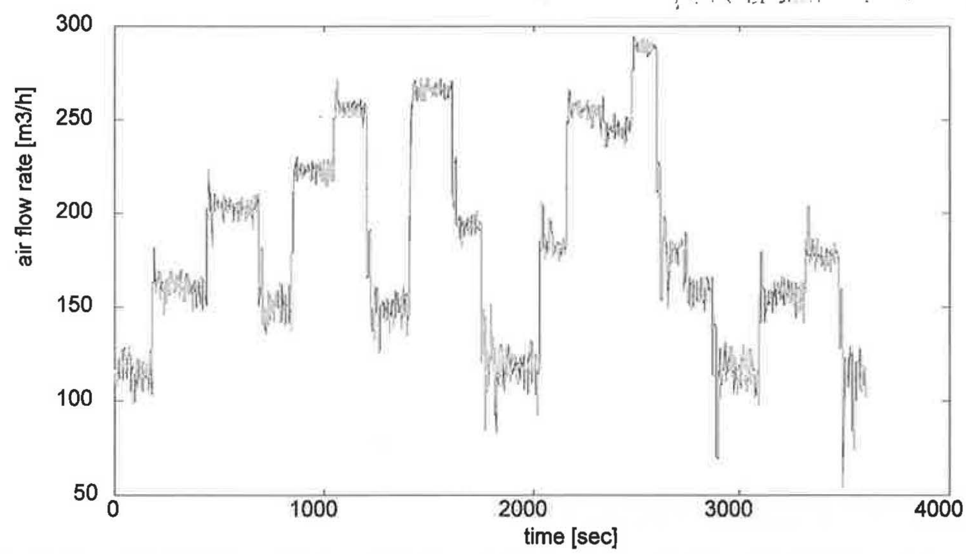


Figure 7.1: Non-linear variations of the ventilation rate during a validation experiment.

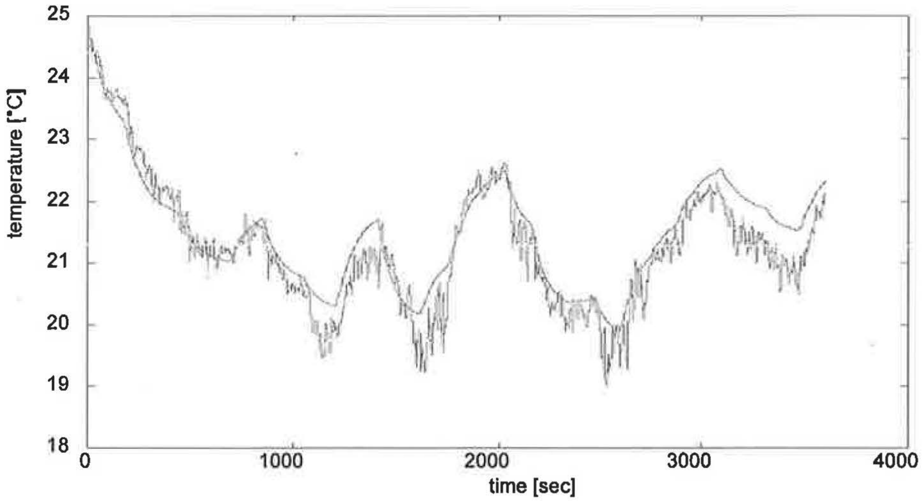


Figure 7.2: The predicted temperature compared to the measured temperature at sensor position [421]. The mse is 0.34 °C.

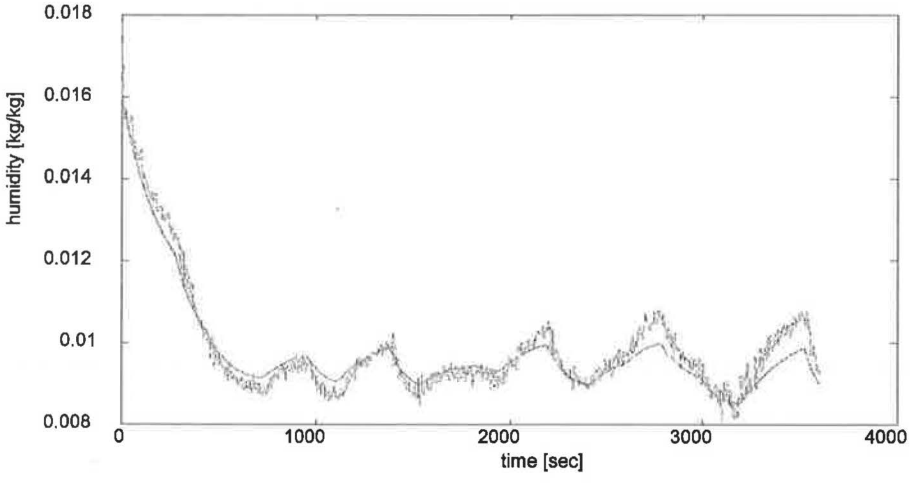


Figure 7.3: The predicted absolute humidity compared to the measured absolute humidity at sensor position [421]. The mse is 0.63 $g_{water}/kg_{dry\ air}$.