Energy Impact of Ventilation and Air Infiltration
14th AIVC Conference, Copenhagen, Denmark
21-23 September 1993

Visualization of Measured Three Dimensional Well Mixed Zones of Temperature in a Ventilated Space

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De Moor Maarten[1], Berckmans Daniel[2]

Abstract

A new model concept has been developed to model the three dimensional energy and mass transfer in an imperfectly mixed fluid. The model permits to predict the dynamic behaviour of the volumetric concentration of heat flow, mass flow and fluid flow. A laboratory test installation has been built to analyse the model capabilities to predict the dynamic behaviour of the air flow pattern within a ventilated space in order to control the energy and mass transfer in the ventilated space. This test installation permits to measure and to visualise well mixed zones of mass and energy concentration and gives the opportunity to visualise the air flow pattern in a quantitative way. Experiments have been done with this test installation in order to test the model concept.

The objective of this paper is to explain the possibilities of the test installation and the different measurement techniques that are used. Furthermore, experimental results will be given.

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1. Introduction

Mathematical models of physical phenomena are a basis for predicting the dynamical process behaviour and are essential in the design of optimal control strategies for these processes. In many processes the control of heat and mass transfer presents a major problem. A missing link is a reliable mathematical model for the dynamic behaviour for the dynamic fluid flow pattern in an imperfectly mixed fluid.

At present, mathematical models for fluid flow pattern are typically based on a discretisation of the physical laws that govern the behaviour of the fluid under study. The method is based on the classical approach of mass, momentum and energy balances (the so called white box modelling approach), which typically leads to partial differential equations such as convection -diffusion equations, Navier-Stokes, etc. The partial differential equations involved are conservation and continuity laws for momentum, enthalpy and mass flow. These are applied to one or more discrete volumes chosen to represent the system under study, i.e. the equations are discretized on a grid both in time and space and on each point of the grid the state is calculated, typically by solving immense sets of linear equations at each time step.
Such models are currently available for contaminant dispersal analysis, steady fluid flow analysis and thermal analysis. An important advantage of this modelling approach is the fact that reliable simulations are possible which are based on physical insight. There are still many technical and fundamental problems for classical computational fluid dynamics models. Some of the disadvantages are:

- Existing modelling techniques are mainly developed for simulation in steady state. For control purposes however, the dynamic behaviour of the process subject to variations is to be modelled.
- Because of the number of grid points that is used, typically there is a model validation problem to verify whether the model is sufficiently accurate for the control purpose at hand.
- The approach does not allow to model the dynamic behaviour of the three dimensional fluid flow pattern.
- The boundary conditions must be known before a model is useful

2. Objectives

Our overall hypothesis is that the fluid flow pattern generates a heat and mass transfer with resulting micro-climate conditions.
The central objective of this paper is to demonstrate the capabilities of the test installation to visualise well mixed zones of temperature. Furthermore it is the objective to demonstrate the capabilities of the test installation to visualise and quantify the air flow pattern. It is the aim to demonstrate by experimental results that there exist a relationship between the distribution of energy in a confined space and the resulting air flow pattern.

3. Measurement set-up

In order to develop and validate different model- and control strategies, a test installation was built to measure the three dimensional distribution of temperature and humidity and to estimate the dynamic behaviour of the volumetric concentration of heat flow and the mass flow and the fluid flow pattern as well. In this section a brief overview will be given about the capabilities of the test installation and the experimental conditions will be explained. The test installation has been described in more detail in literature (Berckmans et al., 1992).

3.1 The test chamber

The purpose for which the test chamber was built, is to generate stable air flow patterns and to measure the transient behaviour from one stable air flow pattern to another. It is indeed mentioned in literature (Barber and Ogilvie, 1982) that the fluid flow pattern plays an important role in the basic mechanism of energy and mass transfer within a fluid. The type of resulting fluid flow pattern will be determined by the characteristics of the used test room such as (Croom-Gale et al., 1975): geometry of the test room; geometry, dimensions and position of the air inlet; geometry, dimensions and position of the air outlet; temperature of the surrounding walls; temperature difference between the incoming air and the air in the test room; inlet velocity of the

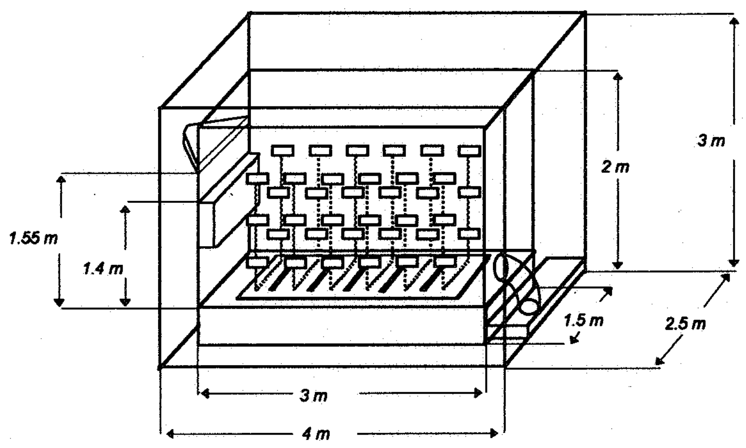
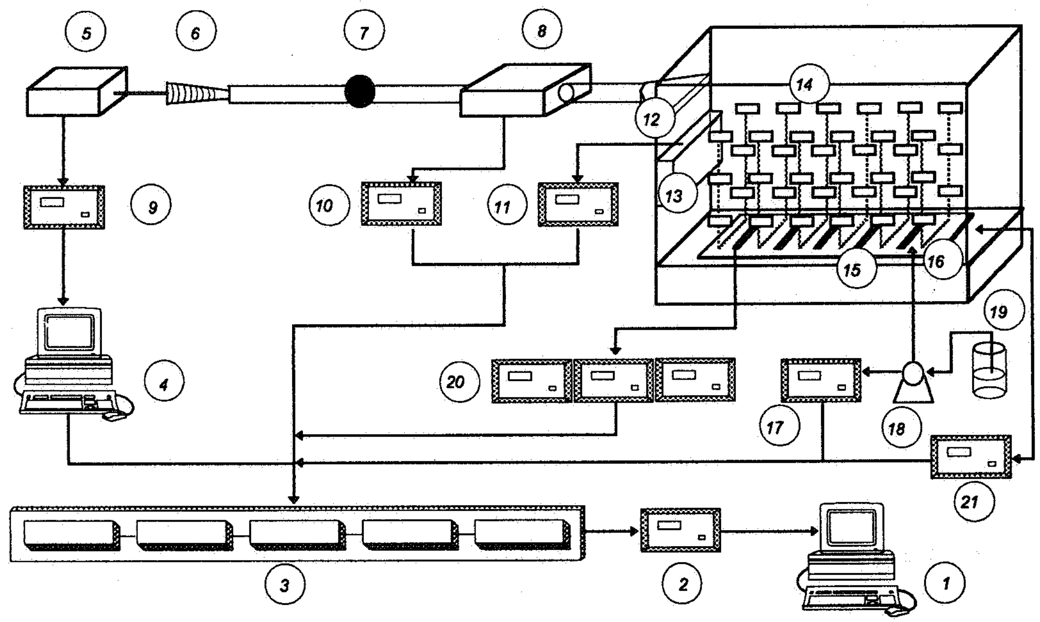


Figure 1: Dimensions of the test installation



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. **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 2: Schematic representation of the different parts of the test installation

incoming air; turbulence of the air within the test room. Considering the conclusions in literature (Leonard, Mc, Quitty, 1985; Mullejans, 1966; Randall, Battams, 1979; Randall, 1979; Regenscheit, 1970) the following room geometry was taken: length = 3 m, width = 1.5 m; height = 2 m. To minimize the disturbing influence of the walls on the air flow pattern as caused by the surface temperature of the walls, a second building envelope (also in Plexiglas) was built around the primary test room. The different dimensions, geometry's and positions are shown on figure 1.

3.2 Measurement of the different input- and output variables

The input variables as measured in the test chamber are (figure 2):

- the air flow rate
- the temperature of the incoming air
- the relative humidity of the incoming air
- the amount of heat supplied to the test chamber
- the internal heat production
- the internal moisture production
- pressure difference between the test chamber and the envelope

The considered output variables are:

- the temperature and relative humidity of the internal room air
- the quantified air flow pattern
- the three-dimensional distribution of the temperature and humidity

For a more detailed description of the measurement method, we refer to Berckmans et al. (1992).

4. Method: Model concept

According to what has been shown in literature (Berckmans, 1989; Timmons, 1980; Randall, 1979,1981), the total volume of a ventilated space is considered to be a non-perfectly mixed air space. Consequently it is assumed that there is a three dimensional air flow pattern in the building volume and (related) gradients in the local micro-environmental parameters (temperature, humidity). Although the building is considered to be a non-perfectly mixed air volume in this model concept, it is always possible to define a *control volume* or a well mixed zone as being the maximum three dimensional volume in which, by definition there is well mixed air. This means that within this control volume there are no gradients of temperature, humidity, gas concentration, air velocity etc. Consequently from the theoretical viewpoint this control volume is supposed to be infinitely small. It will be shown by experimental results that in reality this is not the case. When this concept is applied in reality the perfectly mixed volume indeed is a better mixed zone with acceptable gradients as dictated by the application.
In the model concept there are two types of input variables: the global inputs and the local inputs (see figure 3). Initially the global inputs are ventilation rate V through the test installation and the heat supply Q from the heating system to the test installation (see figure 2). In addition to these, the local inputs to the control volume are the part Vc of the global ventilation rate that enters the control volume, the part Qc of the total internal heat production Q that enters the control volume and the part Wc of the total mass production that enters the control volume. Applying the law of mass conservation and the general law of total energy conservation on the control volume results in a temperature (T) and humidity (X) equation (Berckmans, 1992):

$$\frac{dT_i}{dt} = -\beta.v_c.T_i + \beta.v_c.T_o + \delta.w_c \qquad (1)$$

$$\frac{dX_i}{dt} = -\alpha.v_c.X_i + \alpha.v_c.X_o + \gamma c_c \qquad (2)$$

In these equation the Greek symbols represent physical constants such as specific heat, specific mass etc. It is important to note that in equation (1)and (2) every parameter has a physical meaning as explained in Berckmans 1992.
As shown in figure 3, the problem can be split up into two steps:

1. Determination of the values of the local variables v_c, c_c and w_c starting from measurement results of the inlet temperature and humidity T_o and X_o and the inner temperature and humidity T_i and X_i. This is a problem of parameter estimation of the model given by equation (1) and (2).
2. Determination of the relationship between the global process inputs V and Q and the three local inputs in the control volume v_c, w_c and c_c. In other words the modelling of the energy and mass transport by the fluid in the three dimensional space to the control volume.

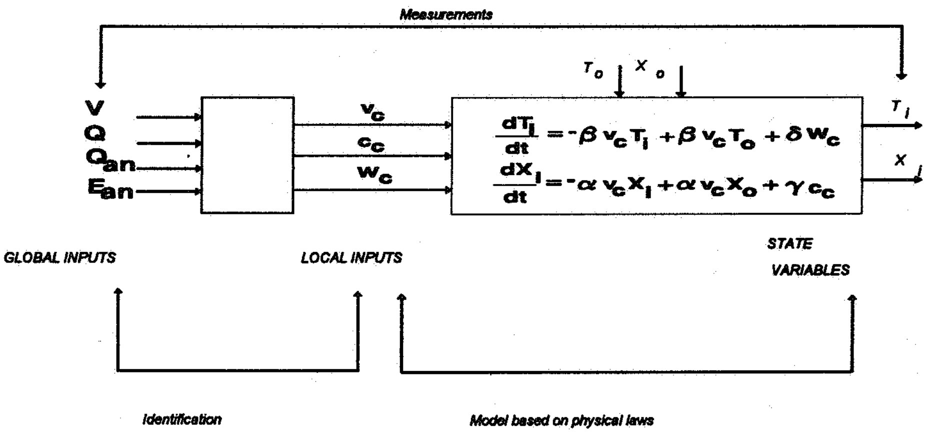


Figure 3: Schematic representation of the two model parts.

5. Results

5.1 Experimental conditions

Since the objective is to model the energy and mass transfer in an imperfectly mixed fluid and to model the dynamic behaviour of the air flow pattern, experimental conditions were chosen in this way that different air flow patterns could be achieved. To generate these different air flow patterns a first set of experiments was carried out with the air flow rate V as the variable input. In table 1, an overview is given of the different experimental conditions that were used with the air flow rate V as variable input. In addition to these, two experiments were carried out in order to investigate the influence of the additional heat supply Q on the resulting air flow pattern. In table 2, an overview is given of the experimental conditions.

Table 1: Experimental conditions for the air flow rate V as variable input

experiment	image	air flow rate (m3/h)	Inlet temperature To (°C)	Internal heat supply Qan
smoke 5	image 1a	88.2439	10.98	112.69
smoke 7	image 2b	158.8432	11.00	34.739
smoke 11	image 4a	244.7467	11.49	14.3350
smoke 14	image 6	308.0871	11.52	9.03518

Table 2: Experimental conditions for the heat supply Q as variable input

experiment	image	air flow rate (m3/h)	Inlet temperature To (°C)	Q
smoke 15	image 7	101.735	10.9	0
smoke 16	image 8	101.671	10.9	0.20

5.2 Visualizing and quantifying the air flow pattern

As been mentioned in literature the process of air mass transport has an important influence on the resulting micro-environment within a building. To achieve an efficient transfer of energy and mass around the occupants, the air flow pattern should be controlled. To study the air flow pattern in a more quantitative way, a technique was developed to visualise and quantify the air flow pattern in a room. The use of a low cost camera is combined with an algorithm on a personal computer to calculate automatically the co-ordinates of an air jet and to visualise the air flow pattern. For a more detailed description of the method used, we refer to Berckmans et al., 1993. To visualize the air jet, a smoke $TiCl_4$ was used. After installing a stable air flow pattern, using the experimental conditions described higher, the resulting smoke pattern was filmed during 15 seconds using a low cost video camera. The higher mentioned technique allows us to determine the two-dimensional coördinates of the centreline of an incoming air jet. In figure 4 the result of this visualiztion method is shown for the experiments described in table 1. In figure 5, the quantified air flow patterns are shown when using the heat supply Q as variable input (experiments in table 2).

Figure 4: The visualized and quantified centreline of the air flow patterns, when the air flow rate V is used to generate different air flow patterns (lower curve: air flow rate = 88 m^3/h, upper curve: air flow rate = 308 m^3/h)

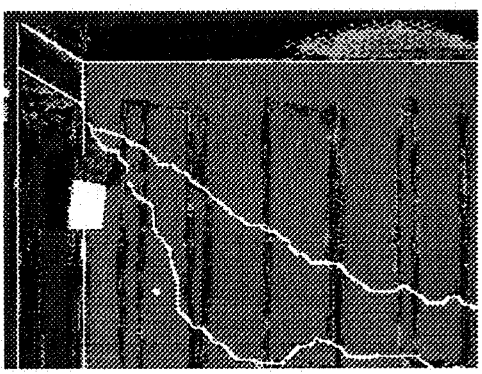
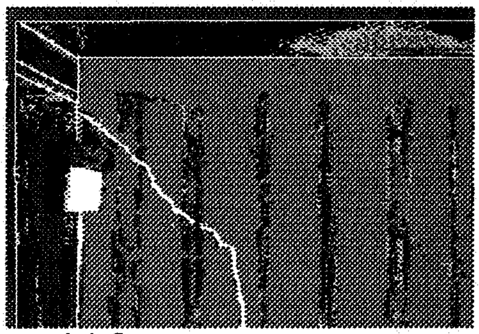


Figure 5: The visualized and quantified air flow patterns, when the heat supply Q is used to generate different air flow patterns (air flow rate constant, lower curve: heat supply = 0 Watt, upper curve: heat supply = 500 Watt).

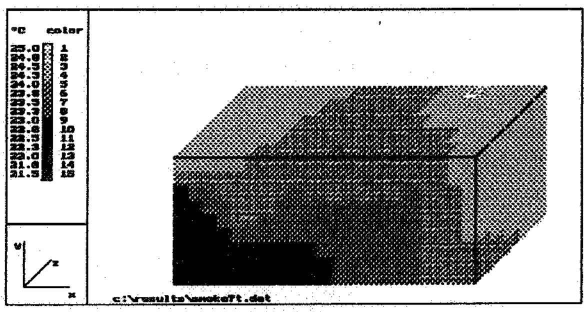
5.3 The relation between the air flow pattern and the three dimensional temperature distribution

As been mentioned before, the building is a non-perfectly mixed air volume and is considered as such in this model concept. Although this fact, it is always possible to define a control volume as being the maximum three dimensional volume in which, by definition there is perfectly mixed air. This means that within this

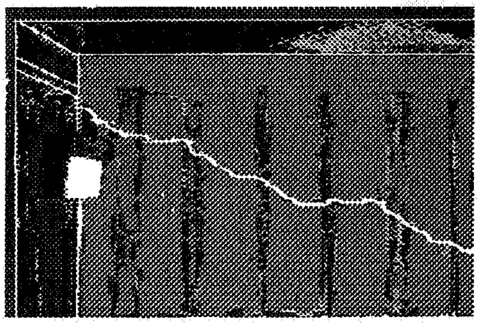
control volume there are no gradients of temperature, humidity, gas concentration, air velocity etc. Consequently from the theoretical viewpoint this control volume is supposed to be infinitely small. It will be shown by experimental results that in reality this is not the case. When this concept is applied in reality the perfectly mixed volume indeed is a better mixed zone with acceptable gradients.
In figure 6 a visualization is given of measured three dimensional well mixed zones of temperature for three different air flow patterns shown in figure 4.



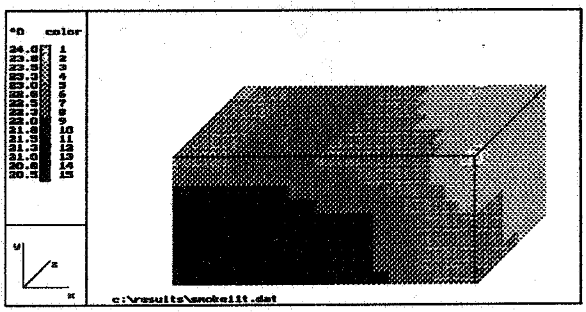
measured air flow pattern



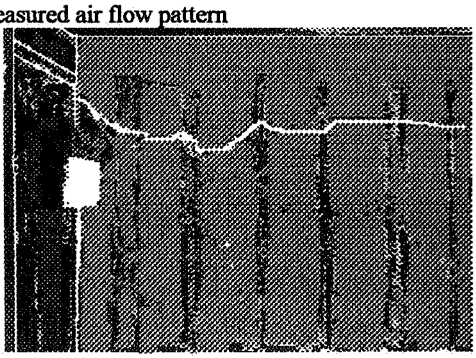
measured control volumes



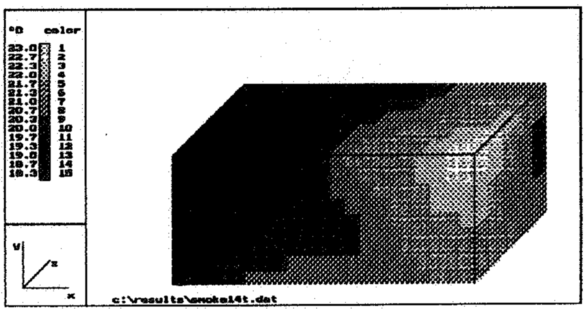
measured air flow pattern



measured control volumes



measured air flow pattern



measured control volumes

Figure 6: The *measured* temperature distribution in the test installation as a function of the *measured* generated air flow pattern (figure 6a: experiment smoke7t, figure 6b: experiment smokel1t and figure 6c: experiment smokel4t).

From this figure important conclusions can be drawn regarding the temperature distribution in a ventilated space as a function of the air flow pattern. When the *temperature gradient* in the test installation is considered, it can be concluded that the temperature difference between maximum and minimum temperature in the test installation is larger with larger values of the air flow rate and dependent of the generated air flow pattern. Regarding the *position* of the control volumes, it can be concluded that for the given experimental inlet conditions (see 5.1) and for low air flow rates (falling air) the well mixed zones of low temperature (in relation to the given scale) are positioned in the lower part of the ventilated space (see figure 6).
For air flow patterns generated using high values of the air flow rate on the contrary, the cold zones will be found in the upper part of ventilated space (see figure 6).

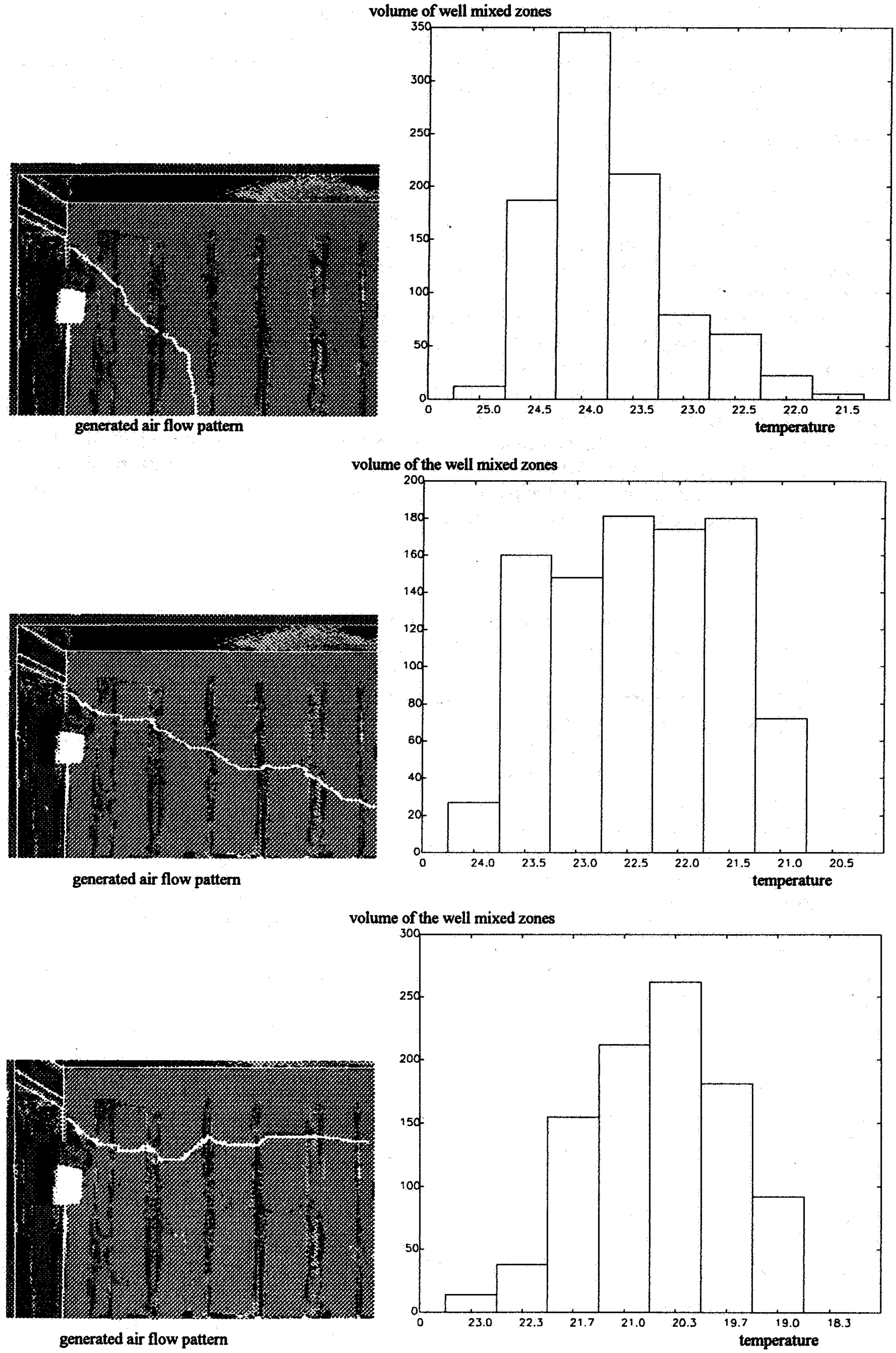


Figure 7: The volume of the well mixed zones (as a function of the temperature) in relation to the generated air flow pattern

When the *size* of the well mixed zones is considered, it can be concluded from figure 7 that for an increasing air flow rate (and so different air flow patterns (figure 7a to 7c)) the largest control volume corresponds to a lower value of temperature. When unstable air flow patterns are installed (figure 7b) it can be concluded that the well mixed zones are equally spread in volume over the volume of the test installation as a whole.

6. Conclusions

In order to develop and validate different model- and control strategies, a test installation was built to measure the three dimensional distribution of temperature and humidity and to estimate the dynamic behaviour of the volumetric concentration of heat flow and the mass flow and the fluid flow pattern as well. In this paper a model concept with the notion of *control volume* was briefly explained. It was shown that the laboratory test room permits one:
- to visualize the well mixed zones with constant temperature as defined in the model concept,
- to visualize the air flow pattern or more specifically: the centreline of an incoming air jet,
- to quantify the three dimensional air flow pattern,
- to do measurements on the steady state and transient behaviour of the inside temperature and humidity to validate the models capacity to predict the air flow pattern.

From experimental results it could be concluded that the air flow pattern plays an important role in the distribution of energy within an imperfectly mixed air volume. Furthermore it was demonstrated that the air flow pattern is of great influence to the temperature gradient in the test installation and to the size and position of the well mixed zones as defined in the model concept.

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