

**TEST INSTALLATION TO DEVELOP A NEW MODEL CONCEPT TO  
MODEL AND CONTROL THE ENERGY AND MASS TRANSFER IN A  
THREE DIMENSIONAL IMPERFECTLY MIXED SPACE.**

**D. Berckmans\* , M. De Moor, B. De Moor\*  
Katholieke Universiteit Leuven  
Belgium**

**SUMMARY**

A new model concept has been developed to model the energy and mass transfer in a three dimensional imperfectly mixed space. The model permits to predict the dynamic behaviour of the volumetric concentration of heat flow and the mass flow and the fluid flow pattern as well. A laboratory test installation has been built to measure the dynamic behaviour of the three dimensional air flow pattern within a ventilated space. These measurements are used to validate the model's capacity to predict the behaviour of fluid flow pattern. The objective of this paper is to describe the test installation and the different measurement techniques being used. By doing so the objective of this research project becomes clear while it shows what data can be generated and used by other research teams.

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### 1. PROBLEM

In the existing literature about the modelling of the response of the micro climate to variations of the control inputs (ventilating rate and heat supply), different quantitative models have been proposed. An important disadvantage of these models is that they have too restrictive constraints to be useful for control purposes:

- In these models the perfect mixing of the room air is supposed [2,3,27].
- The ventilating rate is considered to be constant level or is considered to be a linear function of the room temperature [1,10]. For control purposes however, the air flow rate is the most important non linear control input regarding the micro climate at different positions in the room.

- In the proposed models, only the relatively slow variation in temperature is considered and in most cases the option of constant steady state is chosen [5,6,21].

It is shown that the simulation technique gives an excellent opportunity to get deeper understanding in the dynamic behaviour of physical processes [7,12,28]. Indeed, the knowledge of the physical processes within a system is the essential link to achieve better control. In this purpose, many research has been done to study the dynamic behaviour of air flow pattern within a ventilated space. In most cases the main problem is to generate stable air flow patterns and to simulate physically the dynamic behaviour in a repeatable way and this because of practical considerations. A powerful tool to get deeper understanding in the dynamic behaviour is the visualisation of the air flow pattern and control volumes of temperature and moisture (as defined by Berckmans [4]). The problem here is the gathering of quantitative data. In literature research has been described about the quantification of air flow patterns and the distribution of mass and energy in a ventilated space. Often the flow visualisation is used to get a general, qualitative overview of the flow field.

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Today many models of air flow patterns and room air distribution are developed using the powerful supercomputing techniques [18], while the proposed models only are to be validated with the use of statistical techniques on flow visualisation data.

It is shown that quantitative data (measurements and visualisation of flow patterns) are needed to develop and validate useful algorithms to model the dynamic response of physical micro-environmental factors in an imperfectly mixed fluid.

## 2. OBJECTIVES

By combining the power of on-line modelling algorithms or mathematical identification procedures, with a model, part based on physical laws, the project is focused on the modelling of the physical process of energy and mass transport in a non-perfectly mixed bio-space. The first objective of this paper is to describe the experimental installation and this for several reasons:

- Since a lot of measurements have been realised yet and more will be realised and published, it is important to give a good description of the installation.
- The description of the test installation gives the opportunity for other research teams to propose other experiments.
- The test installation gives the opportunity to visualise fluid flows and distribution of mass and energy in a quantitative way.
- The installation gives the opportunity to test and validate different control algorithms and proposed models.

The second objective is to describe shortly the developed method:

- to visualise the air flow pattern
- to quantify the (dynamic behaviour of) the three dimensional air flow pattern
- to visualise the control volumes (as defined by Berckmans [4]) of inside temperature and humidity.

## 3. METHOD

In following sections different aspects of this test installation will be explained.

### 3.1 THE TESTCHAMBER

The purpose for which the testchamber was built, is to generate stable air flow patterns and to measure the transient behaviour from one air flow pattern to

another. To guarantee stable airflow patterns different parameters must be considered. In literature [8] the following parameters that influence the air velocity and temperature are proposed:

- the geometry of the room
- the geometry, size and position of the air inlet
- the geometry, size and position of the air outlet
- the position of the heat production unit
- the surface temperature of the walls
- the temperature difference between the inside air and the fresh air entering the room
- the velocity of the incoming air
- the turbulence of the inside air

These items will be described in the following sections.

### 3.1.1 The geometry of the room

One of the most important parameters to influence the air flow pattern, is the room geometry. In literature specific scientific research was done on the effect of the room geometry to the air flow pattern. Different researchers [2,3,15,16,17,22] used a rectangular balk with a length-height fraction larger than one. They motivated their choice explicitly or implicitly by referring to real life- and production spaces, whom mostly have an rectangular section. Despite the fact that the length-height fraction is not explicitly included in the Archimedes number [22,23], there is some influence on the airflow pattern. This influence was demonstrated by using the k-epsilon model [20]. Nielsen concluded that an increase of the length-height fraction, decreased the Archimedes number by 20 % only. In literature [26,27] the influence of the length-height fraction was shown on the Coanda-effect. It was demonstrated that the Coanda-effect disappears when the length of the room decreases. Considering these conclusions, the following room geometry was taken (figure 1):

- the length-height fraction must be greater than one, i.e.  $L = 3$  m and  $H = 2$  m.
- the width  $B = 1.5$  m

### 3.1.2 The geometry and position of the air inlet

The position and the geometry of the air inlet are of most importance generating a stable air flow pattern. Consequently different aspects of the air inlet must be taken into account such as:

- the geometric form
- the dimensions
- the position



### *3.1.2.3 The position of the air inlet*

The position of the air inlet above the floor, is an important parameter in realising a stable air flow pattern. In literature [15] it is mentioned that the height above the ground is function of the air inlet velocity and function of the angle of the ceiling in relation to the vertical wall. Different rules are mentioned to define the height of the air inlet. Leonard and Mc Quitty [16], determined that the air flow pattern will attach to the ceiling when the air supply opening is installed on a distance below the ceiling of four times the width of the supply opening. They concluded that no influence was found of the Coanda effect when the air inlet opening was positioned 0.6 m below the ceiling. Their main conclusion was that more research had to be done "to determine the distance of the orifice below the ceiling beyond which jets will not attach...". Based on the experimental testchamber of Leonard and Mc Quitty [16] the air supply opening is installed on 1.55 m above the ground (figure 1).

### **3.1.3 Position of the external heat production**

In literature many research is described regarding the position of the heat supply unit [26] and the influence on the separation point of the air flow pattern. It is concluded that a main influence can be seen on the generated air flow pattern when installing the heating element on the same wall as the air supply opening: the air flow pattern sticks much better to the ceiling when the heat production is turned on. This effect could not be seen when positioning the external heat production on the wall facing the air supply opening. Consequently a heating element (2500 Watt) has been installed under the air inlet. (figure 2)

### **3.1.4 The surface temperature of the walls**

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 is built surrounding the primary testchamber. The temperature in the interspace between the two test chambers is controlled in order to reduce the conduction of heat trough the walls of the internal test chamber.

### **3.1.5 The temperature difference between the inside air and the incoming air**

The temperature of the incoming air is calculated from the corrected Archimedes number to generate a stable air flow pattern. The temperature of the incoming air is controlled by a cooling installation. In this way, it is tried to generate stable air flow patterns when using different inlet temperatures. Indeed, the cooling installation is dimensioned to ensure a range of inlet temperatures to be used.

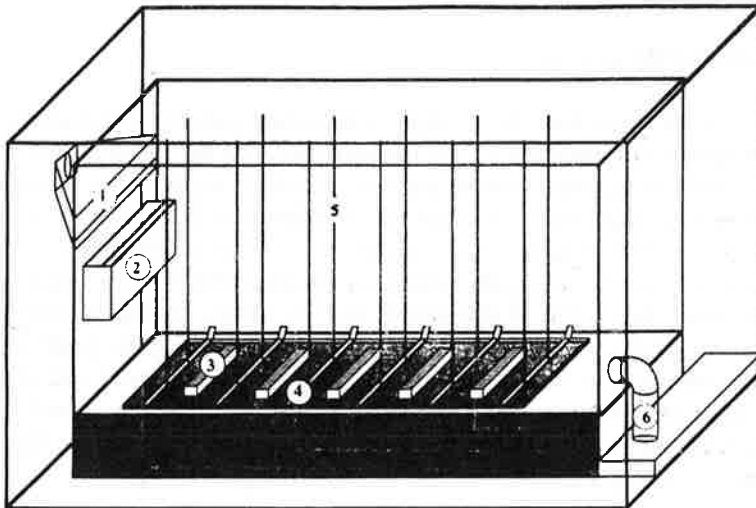


Figure 2: Representation of the different parts in the test installation

1. Air Inlet (slot inlet). 2. External heat production. 3. Internal heat production. 4. Internal moisture production. 5. Support of the temperature and humidity sensors. 6. Air outlet

### 3.1.6 The turbulence of the inside air

Turbulence caused by moving persons or animals and chinks are not taken into account in this study. The test installation is free of any moving object and of chinks that can cause turbulences.

### 3.2 MEASUREMENT OF THE DIFFERENT IN- AND OUTPUT VARIABLES

The input variables as measured in the testchamber are (figure 3):

- air flow rate
- temperature of the incoming air
- relative humidity of the incoming air
- heat supply
- internal heat production
- internal moisture production
- pressure difference between the testchamber and the envelope

The considered output variables are:

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



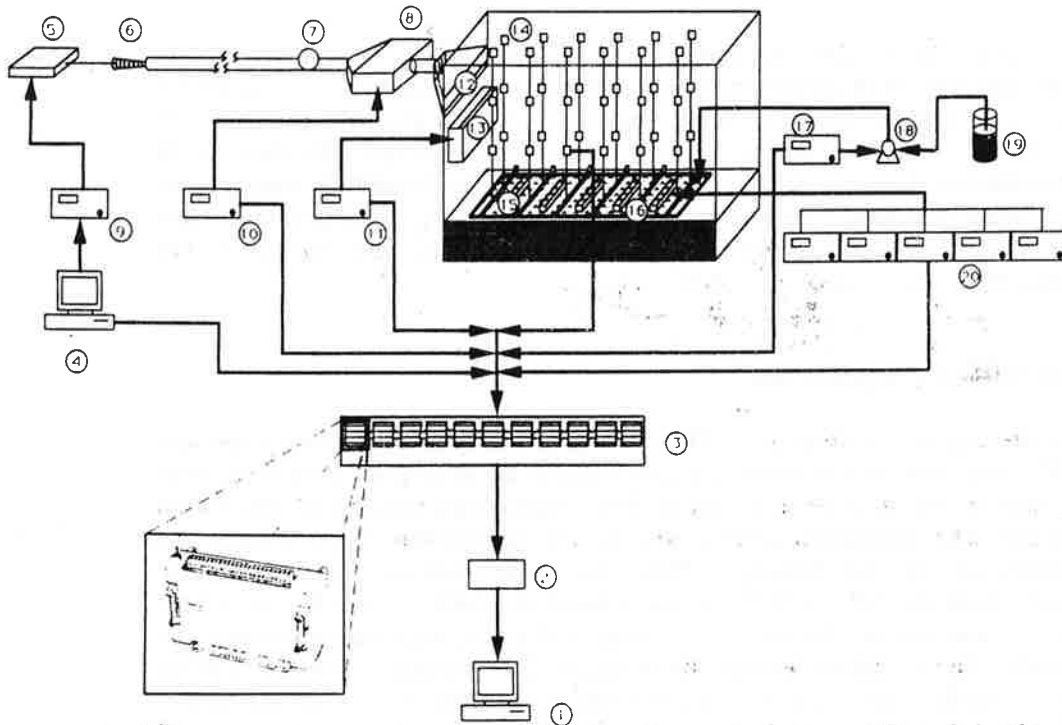


Figure 3: Schedule of the test installation

1. Minicomputer (monitor, floppy disc, to store and visualise the measured data). 2. Parallel-interface for digital and analog 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 testchamber 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 heatsinks 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.

### 3.2.1 Measurement of the air flow rate

To measure the air flow rate a sharpened orifice is used. By measuring the pressure drop over this orifice, the air flow rate is calculated. The orifice was constructed and built accordingly to the international standards DIN 1952 and NBN 688 [9,19]. To produce the desired air flow rate, a cone is used as a diaphragm. This cone can be positioned by steering a stepmotor (figure 3). In the control system the measured air flow rate is calculated using the air temperature, the relative humidity of the air and the atmospheric static pressure. The system of air flow rate production and measurement has an accuracy of  $6 \text{ m}^3/\text{h}$ .

### 3.2.2 Internal heat production

The amount of heat supplied to the room can be varied between 100 and 600 watt [24]. It has been tried to reduce the dimensions of the heating elements in an effort to minimize the obstructions for the air flow. Conventional solutions to simulate the internal heat production, therefore were not appropriate. To determine the temperature of the heating surface, one must consider the physiological implications. Randall [21,22,23] simulated living occupants by using butylsacs filled up with warm water. The surface temperature of his "animals" varied between 28.5 and 39.5 degrees Celsius. Based on literature [13,16] a surface temperature of the heating surfaces of 30.5 degrees Celsius was to be taken. To provide this surface temperature and a maximum surface-volume ratio, it was decided to built aluminium semiconductor heatsinks. On these heatsinks low voltage power resistors were installed to dissipate the desired heat. By measuring the supplied power to these resistors a global measurement of the internal heat production became possible. The measurement and production of the internal heat production has an accuracy of 1 Watt.

### 3.2.3 Internal moisture production

The production of moisture in the testchamber was conceived by indirect heating of water. A streamer with hot water, with a diameter of the tubes of 4 mm, built in a specific form to provide maximal heat dissipation to the surrounding water, is placed in an undeeep water-reservoir ( $0.03 * 1.80 * 1.40 \text{ m}$ ). Using this system it becomes possible to evaporate a large quantity of water in an homogeneous way by covering a large surface. The control of the water flow to be evaporated is done by measuring the level in the water reservoir. The water supplied to the reservoir, to maintain the desired level, is weighted. In this way the quantity of evaporated water during the experiment can be measured. Controlling the amount of evaporated water can be

done by controlling the inlet temperature of the hot water or by regulating the flow rate of the water in the streamer (figure 3).

The flow rate of the water can be installed at different levels, varying from 0.3 l/h to 1.3 l/h. The maximum inlet temperature of the water in the streamer is 55 degrees Celsius. When this temperature is used to evaporate water in the reservoir, the amount of water evaporated is 0.5 l/h.

### **3.2.4 Measurement of the temperature of the inside air**

A previous survey about the appropriate sensors to measure the temperature resulted in the choice of thermocouples. These sensors did meet the following characteristics:

- low response time
- good linearity
- high mechanical strength
- long life time
- minimal dimensions to reduce air flow pattern obstructions

Taking into account these specifications, a thermocouple type EJ-P (Constantan-Chromel) was selected. The accuracy is  $\pm 0.1$  degrees Celsius. The time constant is less than 1 second.

### **3.2.5 Measurement of the relative humidity of the inside air**

The specifications postulated regarding the choice of the humidity sensors were:

- measurement accuracy of 5 %
- low response time (time constant less than one second)
- good repeatability and stability
- minimal dimensions
- simple calibration

Following these conditions, relative humidity sensors (Transmicor 131) based on a change of electrical capacity, were chosen. The sensors were calibrated using a calibration installation shown in figure 4. To install different levels of humidity several salt solutions were used. By solving salt in water the vapour pressure reduces [14]. The salt solutions were conserved in airtight PVC-containers. The different transducers were installed above the salt solution in the PVC-container and the resulting current was measured. In this way, calibration curves were determined given the relation between humidity and output current or output voltage. Using this

calibration method, it could be deduced that the R2 of the linear function that exist between the output voltage and the measured humidity was 0.99 as an average and that the sensors have a statistical accuracy of  $\pm 2.25$  % Relative Humidity. The calibration curve for each individual sensor is used in the datalogger.

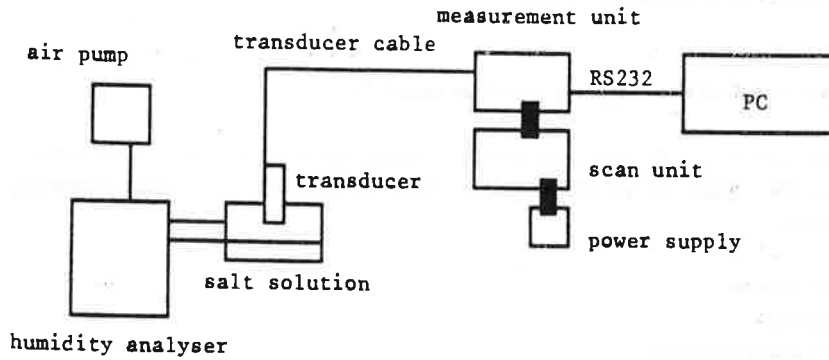


Figure 4: Calibration installation used to calibrate to humidity sensors

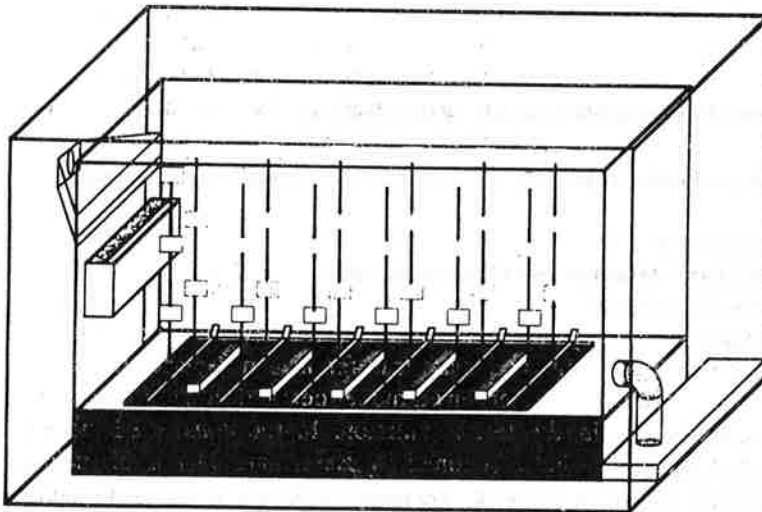


Figure 5: Representation of the sensor positions

### 3.2.6 Supports of the sensors

The total number of sensors in the testchamber is 144, positioned in a three dimensional grid of 72 measuring points. Each measuring point is provided with a temperature sensor and a relative humidity sensor since the model uses an energy and mass equation. Sensors are installed in four equidistant planes above the reference plane, using 18 Inox aerals, divided in three rows of 6 aerals. To whole system is self supporting which means that any connection to the walls of the testchamber is avoided (figure 5).

### 3.2.7 Data-acquisition

The data-acquisition is achieved using an intelligent measurement and data collection unit developed for industrial and scientific data acquisition applications. This data acquisition system can measure different variables:

- DC-voltage
- DC-current
- Temperature (thermocouples)
- Strain Gauges
- Digital inputs

The measurement is carried out by a analog to digital convertor that can be programmed to provide either 16 or 14 bits of resolution and is sensitive to 0.625 microvolt. Measurement speed can be programmed from 40 readings/sec to 400 readings/sec with associated degradation in noise rejection and resolution. All the channels of the datalog system can be controlled individually and configurated using tailor made software (figure 3).

## 3.3 VISUALISATION OF THE ACQUIRED DATA.

The analysis of the measured data will consist in testing the new model concept to model the three dimensional energy and mass transfer in a non-perfectly mixed fluid. Any physical interpretation of a conceived model demands a deep insight in the processes that take place in the test installation. In the considered model concept the notion of control volume (defined by Berckmans [4]) is of major importance. At the laboratory of Agricultural Buildings Research software has been developed to visualise the measured data in three dimensions, to show the control volumes of humidity and temperature, and to visualise the dynamic behaviour of these control volumes as well. An output of this computer program is shown in figure 6.

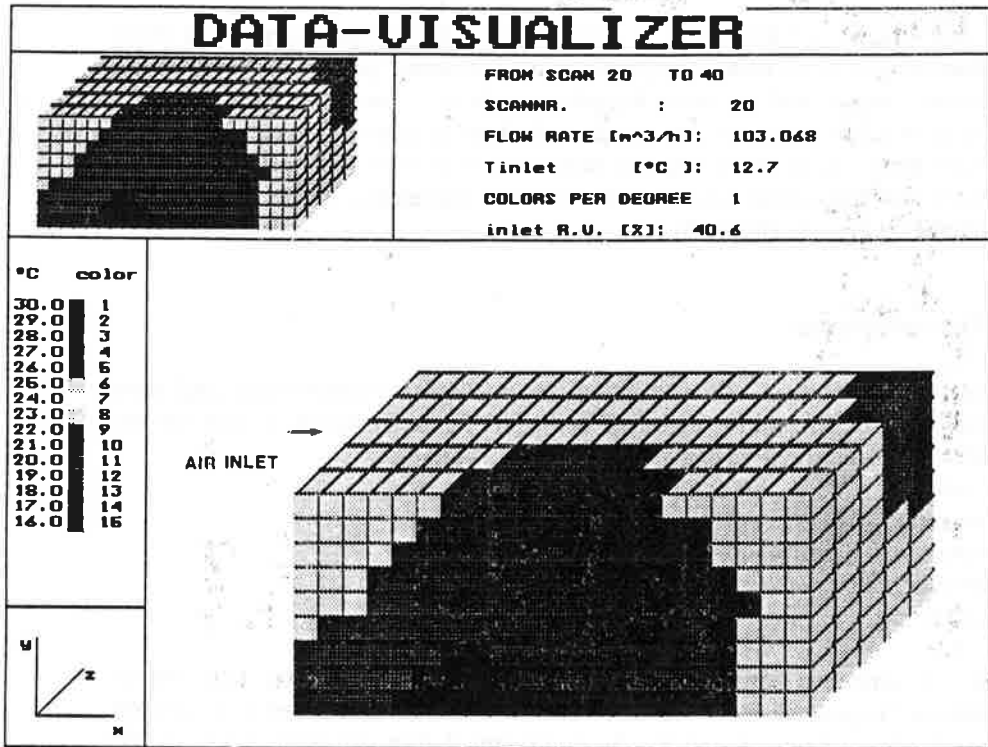


Figure 6: Visualisation of the distribution of the room air temperature

#### 3.4 VISUALISATION OF THE AIR FLOW PATTERN

One of the strengths of the model concept is the capability of modelling the dynamic behaviour of the air flow pattern. Consequently it has been tried to visualise and to quantify the (dynamic behaviour of) air flow patterns. A previous survey about the methods to visualise the air flow pattern, resulted in using the smoke  $TiCl_4$ . By doing so the air flow pattern can be filmed and the produced images are digitised. Using the digital images of the smoke pattern, it is possible to quantify the generated airflow pattern by calculating the centerline of the visualised air flow patterns. In this way, different air flow patterns can be quantified, can be compared to each other and finally can be checked with the measured data. The developed procedure can be used for steady state air flow patterns and for transient behaviour as well.

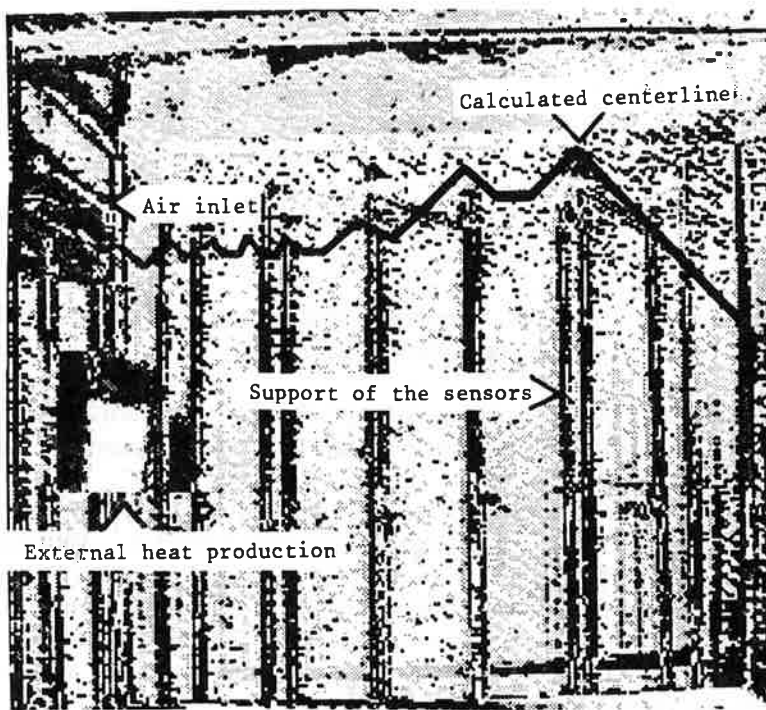


Figure 7: Output of the air flow visualisation program with the calculated centerline

#### 4. CONCLUSIONS

A new model concept has been developed to model the energy and mass transfer in an imperfectly mixed fluid [4]. The model permits to predict the dynamic behaviour of the volumetric concentration of heat flow, mass flow and the fluid flow pattern as well. Therefore a laboratory test room has been built:

- to visualise the control volumes as defined in the model concept [4]
- to visualise the air flow pattern
- to quantify the three dimensional air flow pattern
- to do measurements on the steady state and the transient behaviour of the inside temperature, humidity and air flow pattern to validate the models capacity to predict the air flow pattern.

The measurements, backed up with a quantitative visualisation of the fluid patterns and distribution of mass and energy in the test chamber, permit to gain deeper understanding in the physical processes behind the dynamic behaviour of air flow patterns, in relation to the room air distribution.

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