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INSTRUMENTATION FOR THE MEASUREMENTS OF FLOW, TEMPERATURE AND IMPURITY CONCENTRATION FIELDS

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Introduction

Full-scale testing is an important technique when investigating the performance of ventilation systems for controlling indoor air quality and thermal environment. Because of extremely complicated nature of air flow phenomena and contaminant dispersion sophisticated instrumentation for the measurement of spatial distribution of air velocity, turbulence intensity and contaminant or tracer gas concentrations is needed. During the last decade a number of different simulation models for air flows and indoor air quality have been introduced (1,2,3). The final validity of a model is justified with empirical verification, i.e. by comparing the predictions of the model with physical reality. Empirical verification of the model presupposes, however, that high quality data of the characteristics of air flow, contaminat or tracer concentrations, temperature distributions and room geometry is available. Therefore in ventilation research there is an increasing need to take into use test spaces with advanced instrumentation.

For verification of the relevance of the model experimental data should be available from the entire test space. This means that a dense grid of measurement points must be used. In practice a measuring robot is needed for traversing the transducers. To be able to perform such comprehensive measurements reliably in routine manner and with reasonable amount of work a computer controlled data acquisition system is also necessary. High quality graphics software is crucial when the measured three-dimensional data is presented as distributions.

The project was carried out in the Laboratory of Experimental Occupational Hygiene of Turku Regional Institute of Occupational Health. The ventilation laboratory was built for research and test measurements of different ventilation systems for controlling indoor air quality and thermal environment. The planning of the laboratory was started in 1986 by visiting several ventilation laboratories in Finland and Sweden. The laboratory was constructed during1986-88, after which the ventilation and measuring systems of the laboratory were built. Principal design of the measuring robot was done in 1987, final design in 1988-89 and construction and programming in 1989. The first measurements were carried out in November 1989.

The aim of this study is to give a general description of the laboratory and measuring system, present some preliminary data of the properties of the system and show demonstrative results of the use of the laboratory.

Laboratory Hall and Ventilation Equipment

The floor area of the laboratory hall is 8 x 13 m^2 and the height is 7 m enabling thermal stratification studies. Three of the walls are inner walls and the fourth wall is provided with special insulation to avoid thermal convection flows near the walls. Cold and warm walls or windows can be simulated with metal surfaces and cooling or heating equipment.

Versatile ventilation equipment is needed in the laboratory to cover different air flow rates, supply air temperatures and humidities. Ventilation equipment of the laboratory consists of supply air unit, exhaust air unit and local exhaust unit. The supply air unit includes heating, cooling, humidifying and filtering units. The fans are driven with frequency controllers. Maximum air flow rate is 3 m^3/s, which gives an air exhange rate of 15 times/hour in the 730 m^3 laboratory hall.

The ventilation control system is a DDC-controller. Fifteen digital regulators are used to control flow rate, pressure, temperature and humidity. The system can be used either manually with a graphic software on a PC or by the measurement computer, which sends commands and reads data through the RS-232 interface.

Measuring System

Basic measuring instrumentation needed in this kind of laboratory includes transducers and analyzers for mean air velocity, turbulence intensity, air temperature, contaminant and tracer gas concentrations, air humidity, air flow rate and pressure. Also flow direction must be measured or visualized. In thermal comfort measurements transducers for radiant and operative temperature are also required.

Measuring Equipment

Requirements for some of the measuring istruments can be found in ISO-standards (4,5,6). For air velocity measurements following requirements and recommendations are given in ISO 7726:

Measuring range:	0.05 - 1 m/s
Accuracy:	± (0.05 + 0.05 v_a) m/s desirable ± (0.02+0.05 v_a) m/s
Response time (90%):	1 s, desirable 0.5 s
Measuring angle:	3 π sr
Integration time:	3 min desirable
Turbulence intensity:	measurement desirable

For air temperature measurements accuracy of ± 0.5 °C is required and ± 0.2 °C is desirable with shortest possible response time. Instruments for measuring air flow rate are described in ISO 5221. Requirements for accuracy of air flow and pressure measurements for testing air terminal devices are given in ISO 5219. Accuracy of air flow meter should be 2.5 % and scale interval of liquid-filled manometer 1.25 Pa (1.25 - 25 Pa), 2.5 Pa (25 - 250 Pa), 5.0 Pa (250 - 500 Pa) and 25 Pa (> 500 Pa). Requirements for humidity and radiant temperature measurements can be found in ISO 7726.

Following instruments and transducers are used for the measurements in the laboratory:

Air velocity, turbulence intensity and temperature:
Dantec 54N10 multichannel flow analyzer, 24 omnidirectional transducers
velocity accuracy: ± 1 cm/s ± 5 %, response time: < 0.1 s
temperature accuracy: ± 0.5 °C, response time: < 1 s
measurement angle: 3.3 π sr
measurement range: 0.05 - 1 m/s (also 0.2 - 5 m/s)

Air and surface temperature:
Craftemp thermistors
accuracy: ± 0.35 °C, response time 6 s

Air contaminant and tracer gas concentrations:
Foxboro Miran 1A infrared analyzer
8-channel air sampling unit (7)
Climet CI-6300 particle counter

Air flow rate:
Halton MSD calibrated measurement wings, accuracy ± 3%
Pitot tube

Pressure:
Alnor MP6KSR micromanometer, accuracy: ± 1%
Micatrone MG1000, accuracy ± 1% of full scale

Relative humidity:
Vaisala Humicap, accuracy: ± 5 %

Measuring Robot

The task of the measuring robot is to move the transducers to collect measurement data of the distributions of air velocity, turbulence intensity, temperature, concentration, etc. from all parts of the test space. The structure of the robot is a combination of following design principles:

Transducers can be moved to every location in the laboratory.

Different kinds of ventilation systems, contaminant/heat sources and objects can be built in the laboratory.

Floor, ceiling and walls of the laboratory must be free for installation of ventilation ducts, supply air devices, machines etc.

The robot should disturbe minimally the air flow field in the laboratory - the structures must be thin and no heat sources or cooling fans are allowed.

The structure of the robot must be rigid in order to avoid vibration, which causes errors to air velocity measurements.

The position accuracy of the system must be better than ± 5 mm.

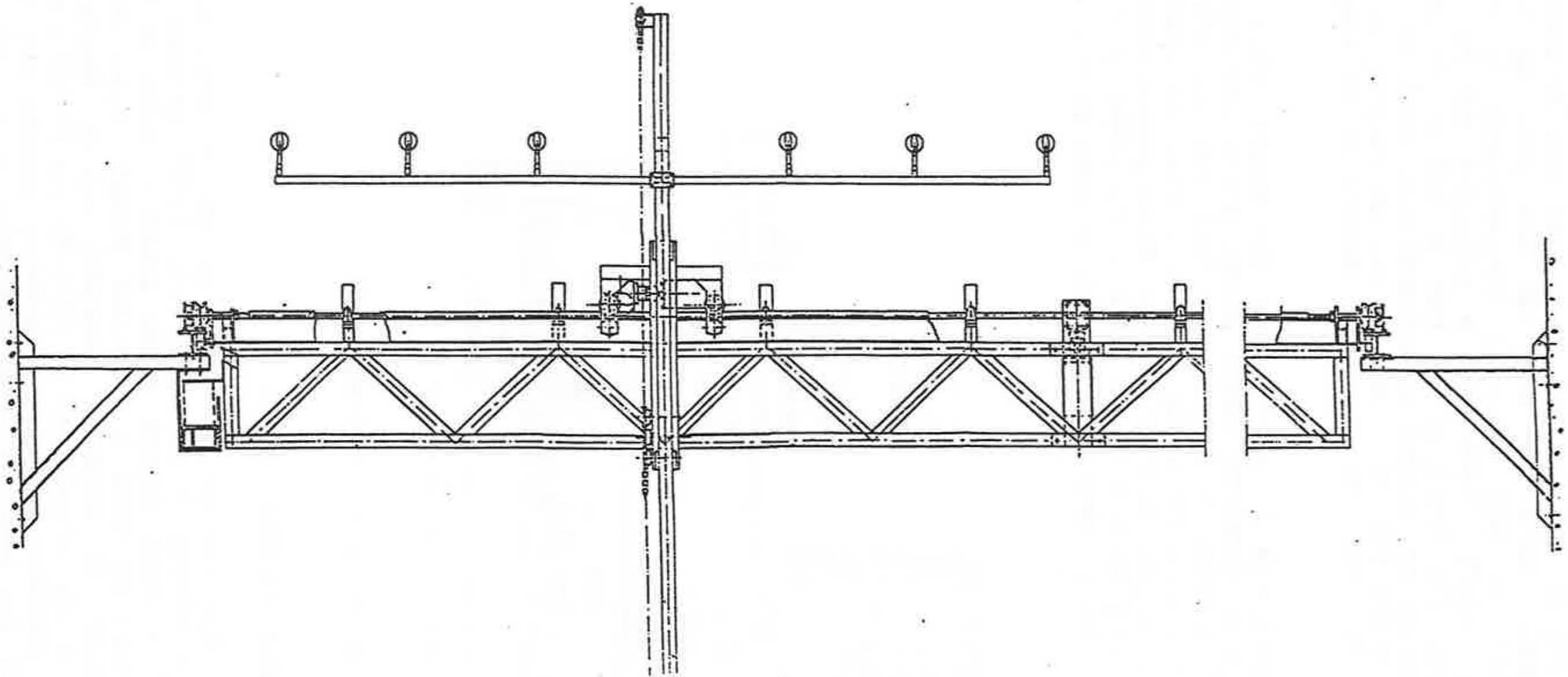

Fig. 1. Mechanical structure of the measuring robot

The structure of the robot is shown in Fig.1. Most design principles were achieved with this model. The supporting rails are located at the height of 3.3 m, which leaves floor and ceiling free. The rails are 60 cm apart from the walls leaving free space for e.g. ventilation ducts. The robot has three parts: the bridge moving horizontally in y-direction inthe laboratory (perpendicularly to the plane of Fig. 1), the carriage moving horizontally in x-direction and the vertical balk moving in z-direction. The length of the balk is half of the height of the laboratory. The transducers are attached to horizontal rods, which can be placed in different heights along the balk. Flow analyzer and air sampling unit are placed on the carriage of the robot. The construction material of the robot is mainly aluminium.

The robot is moved with 3 stepper motors. The stepper motors were chosen because of the following advantages: simple control, precise operation, no cooling fans and power off operation to decrease heat load when not driving. Control diagram of the robot is presented in Fig. 2. Shaft encoders are attached to motor shafts to check the correct movement of the robot. Home position switches are used for checking the absolute position of the robot in the centre of the laboratory. Measurement sequence always starts from and ends in home position.

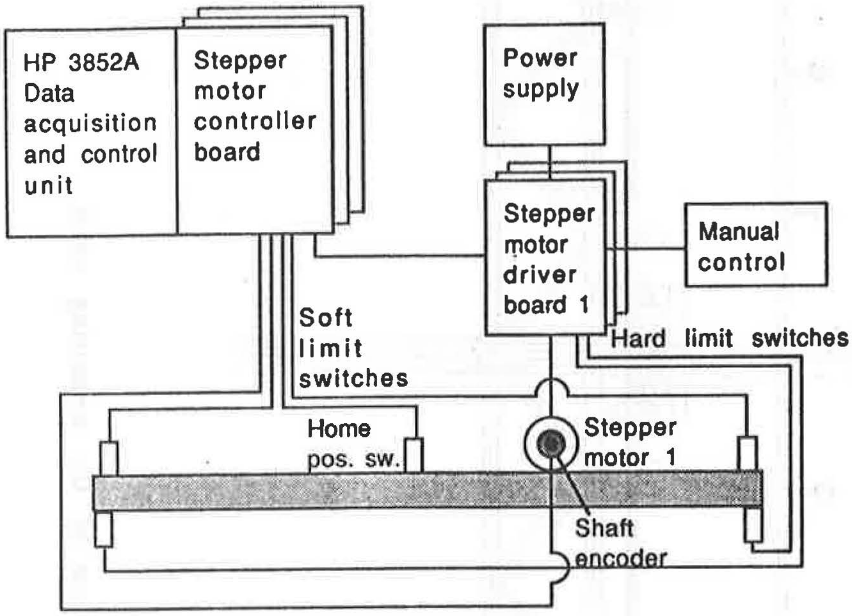

Fig. 2. Control diagram of the measuring robot.

Data Acquisition and Control System

The data acquisition and control system of the laboratory is based on a technical workstation (Hewlett Packard 340) with UNIX operating system and a datalogger (HP 3852A). Block diagram of the system is shown in Fig. 3. The movement of the measuring robot is controlled through stepper motor control board of the datalogger. All measuring instruments and the ventilation control system are connected to the computer through IEEE-488 and RS-232 interfaces. This makes it possible to automatize the whole measurement sequence and to collect all the measurement data and associated setup information in one file, which will have great importance, when managing and postprocessing the large amount of measurement information.

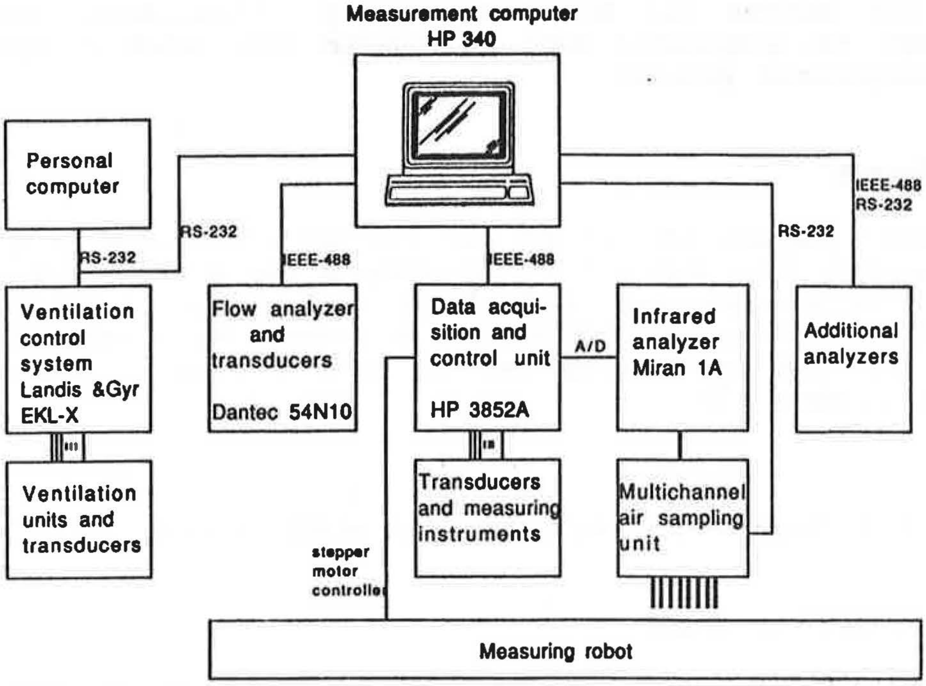

Fig. 3. Data acquisition and control system of the laboratory.

Measuring Software

Special software was designed and programmed to control the measuring robot and to measure concentration, air velocity, turbulence intensity and temperature distributions. The software consists of four main programs:

1. Description of measurement setup
2. Description of measurement route
3. Robot driver and measurement program
4. Data prehandling and transfer to analysis software

Description of measurement setup includes description of the geometrical dimensions of the laboratory (including ventilation ducts, machines and other obstacles), geometry of the three parts of the robot and positions of the transducers in the robot. Descriptions are made with a graphic interface. Setups are stored in files, which are used by the other programs.

Measurement route is described with the second program. It also checks the route for collisions between the robot and laboratory setup. This is accomplished by comparing the positions of all parts of the robot to all parts of the laboratory in all points of the measurement route.

The main measurement program includes definition of the parameters of measuring equipment, active transducers, measuring times etc. After these definitions are concluded the measurement sequence is started. The robot driver program moves the robot to the next measurement point and waits until the measurements are done. It also checks the operation of the robot during the movement. Measurement program controls the flow analyzer, multichannel gas analyzer and datalogger, collects the measurement data from all transducers and stores the data in a file. With the fourth part of the software the measurement data can be prehandled and transferred to the analysis software.

Two additional programs are used in the laboratory for tracer gas measurements and analysis and for datalogger type measurements. All the measuring software was programmed using HP technical basic, which is especially designed for measurement purposes.

Analysis Software

Several analysis programs are available for DOS and UNIX operating systems. The main requirement when selecting analysis software was good presentation of three-dimensional measurement data. SAS-software was selected because of it's versatile graphics procedures. SAS/GRAPH has procedures for interpolation and smoothing of the measurement data and for contour diagrams and three-dimensional presentations (8).

Test Experiments with the Measuring System

Tests of the Measuring Robot

Positioning Accuracy. Positioning accuracy of the measuring robot was tested by moving the robot two meters in all directions and back to starting point. This was repeated 40 times and the deviation of the position from the starting point was measured after 2,4,10,20 and 40 moves. The maximal deviation was in x-direction 1 mm, in y-direction 2 mm and in z-direction < 1 mm. The maximal difference when moving to the same point from positive and negative directions was in x-direction 4 mm, in y-direction 2 mm and in z-direction < 1 mm. Structural design tolerances of the robot were less than .5 mm.

Flow Disturbances. The measuring robot causes some disturbance to the flow field in the laboratory hall. The amount of this disturbance is difficult to quantify, because it varies in different parts of the robot and depends on air velocity and the type of the flow. Preliminary measurements of the disturbace were performed by measuring air velocity in a convective flow caused by one electrical heater of 2 kW placed on the floor. Measurements were done with one transducer attached on a stand at the level 0.5 m above the bridge of the robot (at 3.8 m height). The horizontal distance of the robot from the measurement point, which was in the middle of the convective flow, was varied. Air velocity in free field was 0.55 m/s. It increased by 5 % near the transducer rod, and by 10 % in the worst transducer location in front of the carriage of the robot.

Warming up of the stepper motors is one potential source of disturbing airflows. Surface temperature of the motors was measured during a two hour period with repeated robot movements of two meters in all directions and one minute measurement pause between movements. The power of the motors was switched off as normally after every movement. After two hours the surface temperatures of the motors were about 30 °C. The room temperature was 21 °C. Thermal flow caused by the motors was not significant in the laboratory scale. Normal measurement period is three minutes, which gives three times longer cooling time than in this experiment.

Structural Rigidity. Vibrations of the measuring robot may disturbe air velocity measurements. When the robot is driven to a measurement point it vibrates torsionally, longitudinally and transversally. The excitation of these vibrations is decreased by stopping the robot smoothly. After stopping a certain time has to be waited before air velocity measurement can be started.

After the construction of the robot was finished the vibration level was estimated by eye to be too high. The main vibrations were the torsional vibration around the vertical balk and the vibration of the transducer rods. The design was improved by increasing the width of transducer rods from 20 mm to 30 mm and by adding an alumimium balk with Uprofile on the side of the vertical I-balk. After these improvements the vibration level was found to be considerably lower.

The decrease of the vibration amplitude as a function of time was studied more accurately by measuring the horizontal vibration of the robot using an accelerometer (Bruel&Kjaer 4370), acceleration preamplifier (B&K 2635) and signal analyzer (B&K 2032). The accelerometer was attached with magnet to the outer end of the lowest rod. Measurements were done with the vertical balk in lowest and central positions. These positions were selected to estimate the maximum vibration of the system.

Measured vibration acceleration in the transducer rod of the robot during and after an 11 second movement in horizontal y-direction is shown in Fig. 4. Vertical balk was in central position, which corresponded to the slowest decrease of vibration amplitude. Speed of the robot was 5 cm/s with one second acceleration and deceleration ramps.

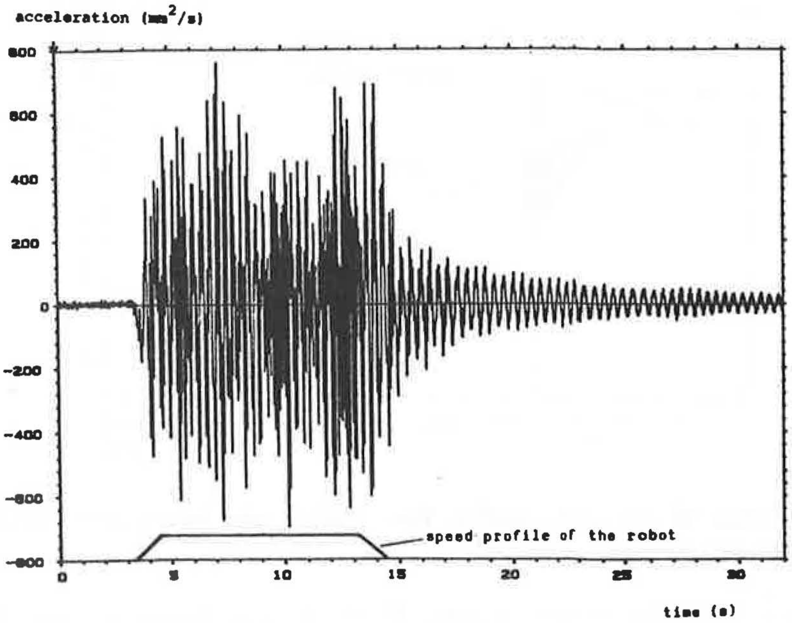

Fig. 4. Vibration of the measuring robot during and after a movement.

The vibration frequencies were studied by spectral analysis using the FFT-analyzer (B&K 2032). During the movement high frequency vibrations were dominant. After the movement the dominant frequency was 3 Hz. Other frequency components were 6,9 and 12 Hz.

Velocity and displacement amplitudes for the dominant 3 Hz frequency were calculated from the measured acceleration amplitudes. Immediately after the movement the values of acceleration, velocity and displacement amplitudes were 0.3 m/s^2, 1.6 cm/s and 0.8 mm. Calculated displacement amplitude of 0.8 mm was checked also visually using a mm-scale. After two seconds the amplitudes were 0.15 m/s^2, 0.8 cm/s and 0.4 mm. Thereafter the amplitude decreased by a factor of 10 in 16 seconds.

It may be concluded, that a sufficient delay before starting air velocity measurement is 10 seconds, which gives a velocity amplitude of 0.2 cm/s (20 % of the error of transducer) and displacement amplitude of 0.1 mm in the beginning of the measurement period. On the basis of the signal analysis the delay time could be limited more, than it would have been possible by only visual estimation.

Test Measurements of Flow, Temperature and Concentration

The whole measurement and analysis system was tested with measurements of air velocity, turbulence intensity, temperature and tracer gas concentration distributions in the laboratory hall. The measurement setup is shown in Fig. 5. Two electrical heaters of 2 kW were used as heat sources. They were placed on a box with dimensions of 1.6 m, 0.4 m and 1.0 m. The tracer gas was nitrous oxide, which was released at constant flowrate of 1.0 l/min between the heaters. Temperature of the supply air was 20 °C. It was blown downwards from 2.5 m height through an open ventilation duct located on a side wall. The outlet was located near the ceiling. Air exchange rate was 2 times per hour.

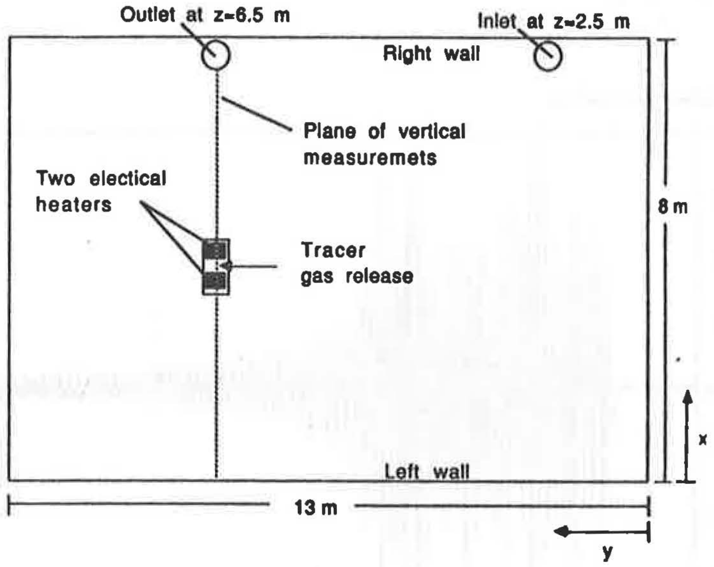

Fig. 5. Location of air inlet, outlet, heat source and tracer gas source in the laboratory hall.

Vertical distributions were measured in a x-z plane above the source using twelve air velocity transducers and eight sampling tubes located in two rods. Total amount of measurement points was 192 for air velocity and temperature and 128 for concentration. Integration time for air velocity was three minutes. The lowest measurement points were at the level of 0.5 m from the floor. The distance from ceiling and walls to nearest measurement points was 1 m.

Original results were transformed to 40 x 70 matrixes using SAS/GRAPH G3GRID procedure with Delaunay interpolation method (8). The matrixes were plotted out as contour diagrams using GCONTOUR procedure. Results are shown in Fig. 6 - 9.

Tracer gas concentration (Fig. 6.) has it's highest values in the convection flow and in the upper part of the hall. Lowest values are found near the left wall and near the source. Concentration in the breathing zone is about 50 % higher near the right wall than near the left wall.

Air velocity contours (Fig. 7.) show the behaviour of the convection flow. It is directed to the left because of the fans of the electrical heaters. Outside the convection flow air velocity is below 0.1 m/s except near the exhaust and near the source.

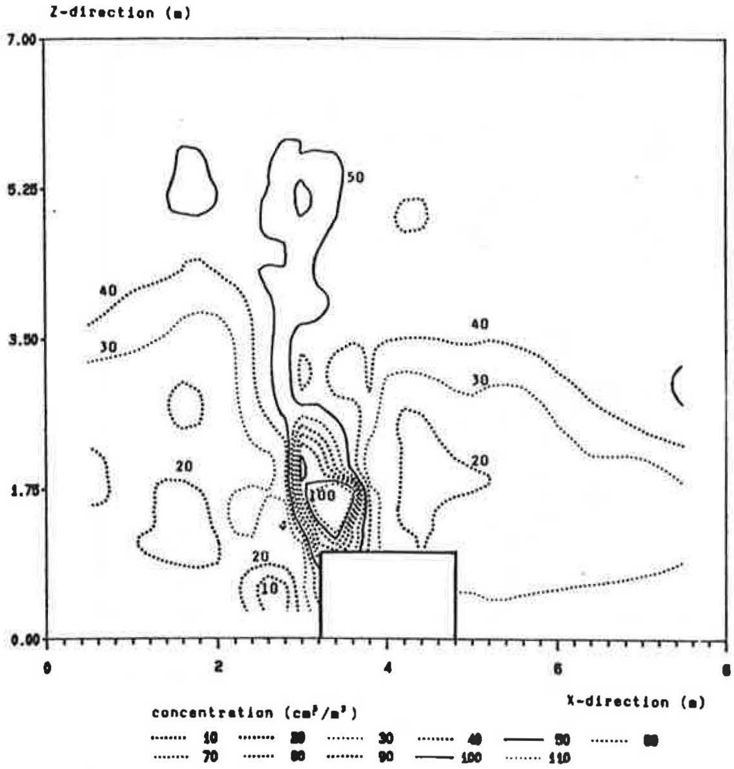

Fig. 6. Distribution of tracer gas concentration in a vertical plane.

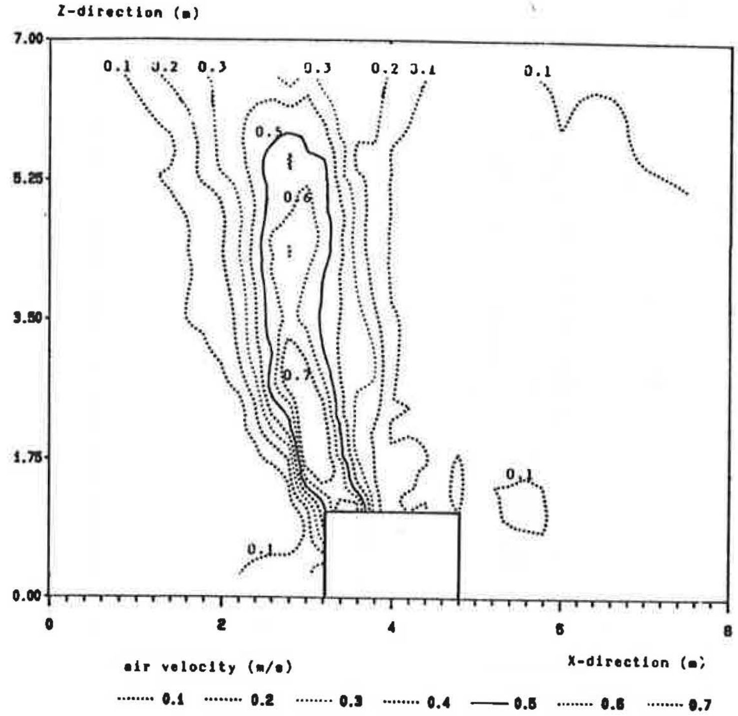

Fig. 7. Distribution of air velocity in a vertical plane.

Turbulence intensity (Fig. 8.) shows high values (over 50 %) on both sides of the convection flow. In the center of the flow the values are lower, between 10% and 30 %. Vertical temperature difference in the hall is only 1 - 2 °C (Fig. 9.). Surprisingly the lowest temperatures are found near the source.

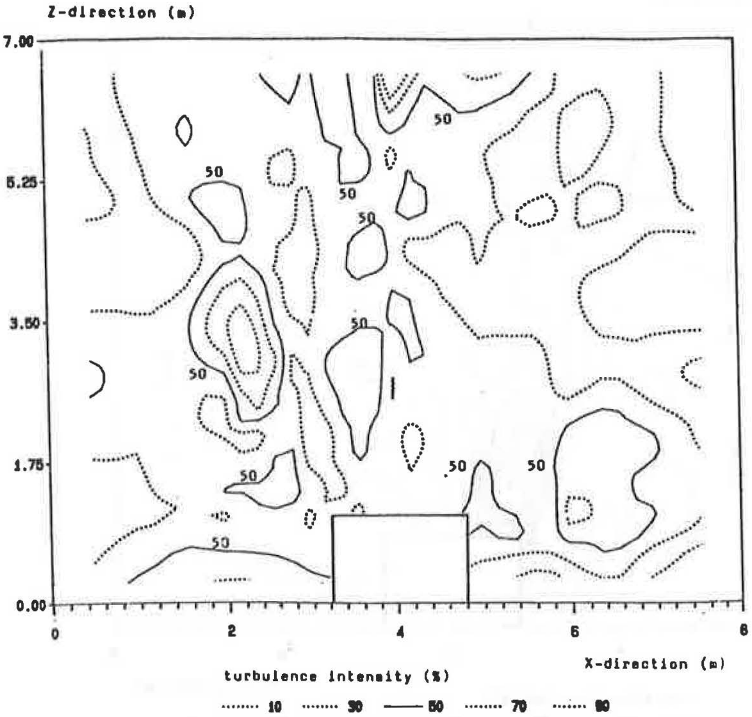

Fig. 8. Distribution of turbulence intensity in a vertical plane.

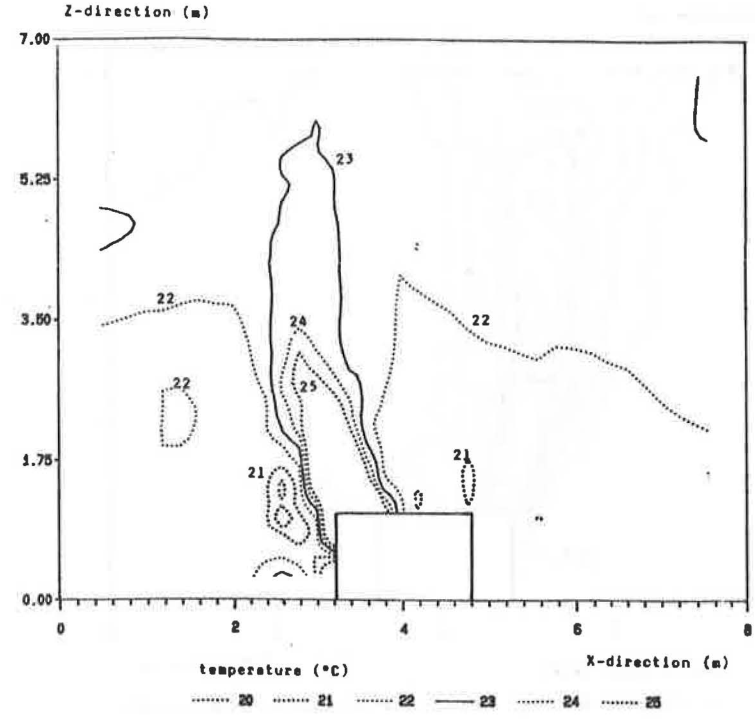

Fig. 9. Distribution of air temperature in a vertical plane.

Horizontal concentration distribution was measured in the breathing zone at 1.7 m level using four sampling tubes. The total amount of measurement points was 96. Distance from walls to nearest measurement points varied from 0.3 m to 1 m. Results were transformed to 40 x 65 matrix and plotted out as a three-dimensional graph using SAS/GRAPH G3D procedure. Results are shown in Fig. 10.

Tracer gas concentration shows it's highest values above the source and near the right wall. Lowest concentrations are found near the left wall. This can be seen also in vertical distribution (Fig. 6.). Local minima are found near the inlet and near the source.

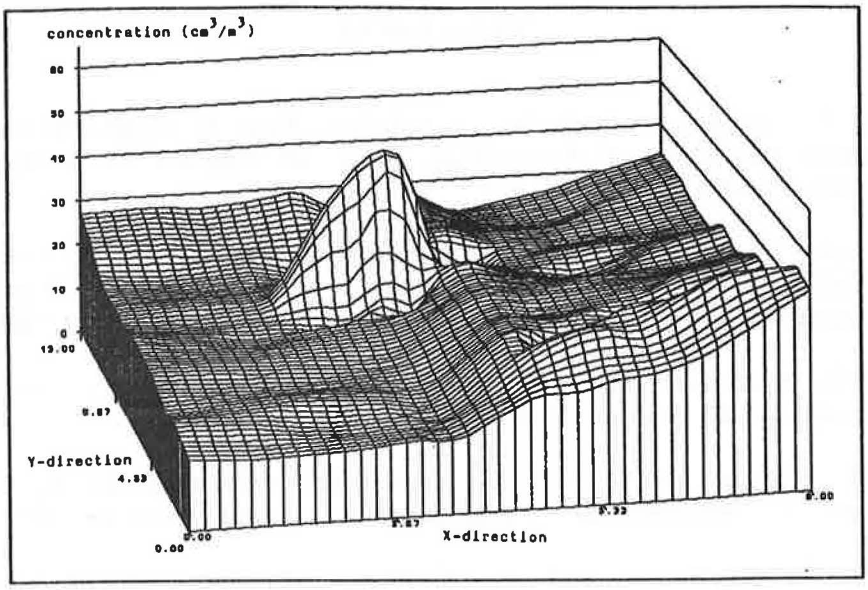

Fig. 10. Distribution of tracer gas concentration in the breathing zone.

Conclusions

The measurement system for full-scale tests has been developed and tested. On the ground of the first measurements the system seems to meet the requirements, that were set when planning the system. Spatial distribution of air velocity and turbulence intensity can be measured even at low room air velocity. Also the concentration field of contaminants or tracer gases and the temperature distribution in test space can be measured.

Measurements can be done automatically with the measuring robot and data acquisition system and software. Errors caused by the vibrations of the measuring robot are negligible 10 s after stopping of the traversing movement. Flow disturbances caused by the structure of the robot were not significant in preliminary tests. Relative positioning errors of the robot were found to be less than 5 mm. Measurement data can be transferred to analysis software to produce graphical presentations of the distributions. The measuring equipment is well suitable for verification of the computer models of air flows and indoor air quality.

Acknowledgments

The authors wish to acknowledge two groups of students and their teachers at the Technical College of Turku for their help in planning the construction of the measuring robot. The company 'Veljet Suomisen Konepaja Oy', especially Mr. M. Laurikainen, is also acknowledged for the final design and realization and 'Barnell Oy' for electrical realization of the robot. The authors want to thank all co-workers in this project at the Institute of Occupational Health, especially Mr. K. Nieminen, Chief of the Information Technology Group and M.Sc.(Eng.) A. Paakkari, Chief of the Tecnical Office.

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SUMMARY

Full-scale testing and numerical simulation are important techniques for investigating the performance of ventilation systems. High quality data of the characteristics of air flow and contaminant dispersion is needed for both full-scale tests and verification of numerical models. A laboratory with instrumentation for measuring distributions of air velocity, turbulence intensity, temperature and contaminant or tracer gas concentrations was developed and tested. A measuring robot is used for traversing the transducers in the 730 m^3 laboratory hall. Main goals in the design of the robot were automatic operation, good positioning accuracy, rigid structure and minimal disturbance of the flow field. A computer based data acquisition system and software was developed to control the robot and to perform the measurements. The measurement results can be transferred to analysis software to produce contour plots and three-dimensional graphs of the distributions. Test measurements were performed to study the characteristics of the system and to demonstrate graphical presentation of the measured distributions. The system was found to be well suitable for full-scale tests and verification of numerical simulation models.