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DETAILED EXPERIMENTAL DATA OF ROOM AIRFLOW WITH DISPLACEMENT VENTILATION

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ABSTRACT

This paper presents a set of detailed experimental data of room airflow with displacement ventilation. These data were obtained from a new environmental test facility at the Massachusetts Institute of Technology (MIT). The measurements were conducted for three typical room configurations: a small office, a large office with partition, and a classroom.

The experiment measured the distributions of air velocity, air velocity fluctuation, and air temperature by omni-directional hot-sphere anemometers and contaminant concentrations by tracer gas at 54 points in the room. Smoke was used to observe airflow. The data include the wall surface temperature distribution, air supply parameters, and the age of air in several locations in the room.

Airflow using displacement ventilation is a kind of mixed convection and therefore, these data are especially suitable for validating Computational Fluid Dynamics (CFD) programs for prediction of indoor airflow.

INTRODUCTION

The indoor environment is important to people's health and welfare because up to 90% of a typical person's time is spent indoors. Our productivity is also related to the indoor environment. The CFD technique has become a popular tool for designing the indoor environment. However, due to some uncertainties in CFD simulation, it is essential to validate a CFD program by experimental data.

Many experimental data are available in the literature but very few of them can be used for validation. In order to validate CFD results, the experimental data must include detailed information of thermal and fluid boundary conditions. The data must also include error analysis. Popular data for validating room airflow are from Cheesewright et al. (1986) and Nielsen et al. (1978). Cheesewright's data are for natural convection and Nielsen's data for forced convection. However, it is still not clear if a CFD program validated by their data can be used for normal room airflow that is really a mixed convection (a combination of natural and forced convection).

This paper presents experimental data for displacement ventilation. Displacement ventilation has been used widely in Europe during the last decade and has received considerable attention recently in North America. As stated, displacement ventilation is mixed convection and presents ventilation reality in many buildings. If a CFD program is validated by experimental data of displacement ventilation, the program should be able to predict most indoor environments, because the flow characteristics of displacement ventilation and other mixing ventilation are similar — both have strong pressure and buoyancy driven flows.

EXPERIMENTAL FACILITY

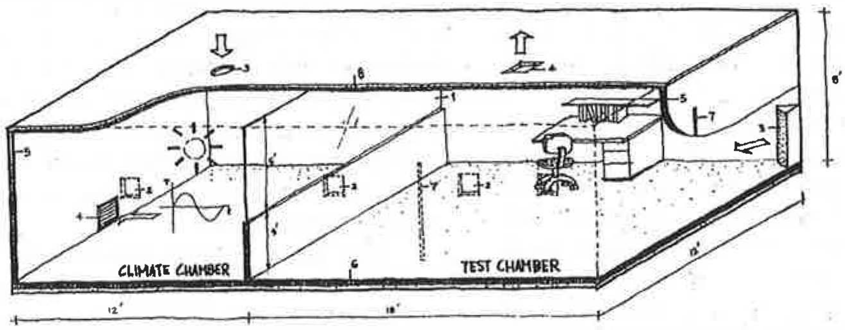
The chambers and HVAC systems

The environmental test facility built at MIT is designed for research and teaching indoor air quality, thermal comfort, energy efficiency, thermal insulation, and Heating Ventilating, and Air Conditioning (HVAC) systems.

The test facility, as shown in Figure 1, consists of a well-insulated enclosure with thermal resistance of 5.3 m^2K/W. Although not shown in the figure, there are doors at the two ends. A movable wall divides the enclosure into a test chamber and a climate chamber. At present, we use the larger one as the test chamber and the smaller one as climate chamber. The lower part of the movable wall is an insulated exterior wall and the upper part is a double-glazing window extended almost the whole width. Table 1 shows the dimensions of the chambers.

The test chamber has two linear diffusers, two circular ceiling diffusers, a grille ceiling exhaust, two flexible displacement diffusers, a grille diffuser installed on the rear wall near the ceiling, and another grille exhaust on the rear wall near the floor. The climate chamber has one ceiling diffuser, one rear-wall diffuser, and one ceiling exhaust, and one rear-wall exhaust. All the diffusers and exhausts can be operated simultaneously or individually in both chambers.

Each chamber has a separate HVAC system. The two systems are nearly identical. Table 1 also shows the capacity of the HVAC systems. Figure 2 illustrates the HVAC system configuration and control interface.



1 - window, 2 – observation window, 3 – air supply diffuser, 4 – air exhaust, 5 – insulated wall, 6 – insulated floor, 7 – light slot, 8 – insulated ceiling

Figure 1. Sketch of the test facility

Table 1 Dimension, thermal resistance and HVAC system capacity of the test facility

Length Width	Height	Test Chamber	Climate Chamber
Dimension	Length	5.16 m	3.08 m
	Width	3.65 m	3.65 m
	Height	2.43 m	2.43 m
	Partition window size	1.16 m high 3.45 m wide	1.16 m high 3.45 m wide
Capacity of HVAC system	Preheater	8 kW	8 kW
	Supply fan	930 m^3/h	930 m^3/h
	Chiller	21 kW for both chambers	
	Reheater	8 kW	8 kW
	Humidifier	11 kg-steam/h	
	Return fan	930 m^3/h	930 m^3/h
	Dampers	930 m^3/h	930 m^3/h

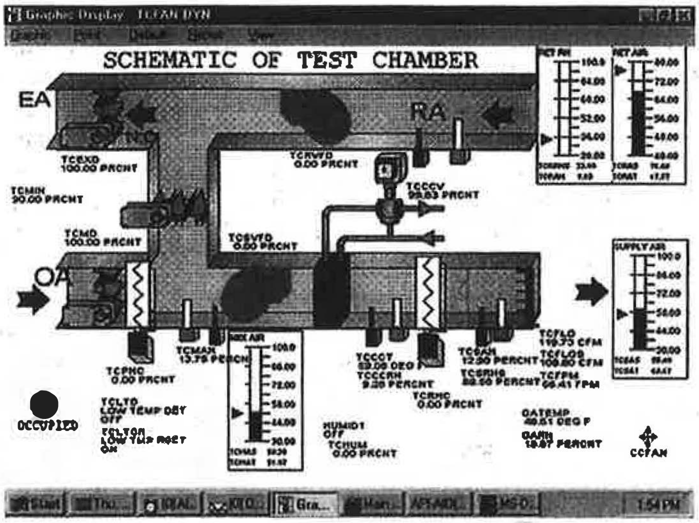


Figure 2. The control interface of the HVAC system

Three louvers control outdoor air rate between 0% and 100%. The supply fan has a variable speed drive. The interface allows an interactive control of the systems. An operator can change any parameters, such as airflow rate, supply and return temperature and humidity by moving the ▶ signs or by typing a number into the appropriate position. The air parameters in different sections of the HVAC systems are shown in the monitor and/or are written into a file in the time interval specified by the operator. Nine-probe hot-wire anemometers, arranged in a matrix form, are used to measure the airflow rate. The HVAC controls air supply rate ranging between 1 ach to 20 ach for the test chamber and 2 ach to 40 ach for the climate chamber.

Equipment

The major measuring equipment of the test facility includes:

- ☞ A flow visualization system for observing air flow patterns
- ☞ A hot-sphere anemometer system for air velocity, velocity fluctuation, and temperature measurements
- ☞ A tracer-gas system for measuring contaminant concentrations and humidity
- ☞ A thermo-couple system for measuring wall and air temperatures.

The test chamber has two long vertical slots and several observation windows on the walls. Light penetrates through the slots and forms a thin light sheet. By injecting smoke into the room, the airflow pattern can be observed through those observation windows normal to the light sheet. We have painted the walls of the room black to enhance visualization effect. The test facility has two types of smoke sources, a theater fog generator and an air current kit. The theater fog generator produces smoke with a temperature far above the environmental temperature. The smoke is cooled through a long tube before entering the room. This generator produces a large amount of smoke to observe how supply air is distributed in the room. However, it is not ideal for visualizing airflow pattern in a particular area. The air current kit remedies the problem. The kit generates a very small amount of smoke locally.

We use hot-sphere probes to measure air velocity, velocity fluctuation, and temperature in the room. The air movement is generally slow in a room with displacement ventilation. The hot-sphere anemometers have great uncertainties for the measurements of low velocities, since natural convection from the hot-sphere produces a false air velocity of the same magnitude. Hot-wire anemometers have the same problem. If a Laser Doppler Anemometer (LDA) is used, substantial time and effort are required to obtain measurements at many locations in a room. There is actually no one ideal instrument for the measurement of low air velocities in an indoor space. The hot-sphere anemometers do not provide reliable results when the air velocity is lower than 0.1 m/s. The repeatability is 0.01 m/s or ±2% of the readings. The measuring errors are ±0.3 K for air temperature, including the errors introduced by the data acquisition systems. Since the probe size is large (about 0.003 m in diameter), the probes are not sensitive to high frequency velocity fluctuation. It is difficult to estimate the errors for velocity fluctuation.

A multi-gas monitor and analyzer system is used to simulate indoor air quality. The tracer-gas system can measure many different types of tracer gases. The present investigation used SF_6 and CO_2. SF_6 is better than CO_2 because the background concentration of SF_6 is almost zero. CO_2 is inexpensive and was used to check the results obtained with SF_6. In addition, we also measured the water vapor concentration for determining relative humidity in the room. The error for measuring concentration is about 5 to 10%.

We also used thermo-couples to measure air temperature and surface temperature of the room enclosures. Many state-of-the-art data acquisition systems use ADD boards. Most of ADD boards we tested have a 0.4 K error and have at least 0.2 K/month drift. Finally, we decided to use a data logger. The error for measuring temperature by the entire system is about 0.2 K.

TEST PROCEDURE

We conducted several measurements with different configurations, such as individual offices, cubicle offices, and classrooms, etc. Figures 3 shows the two-person office configuration used in the experiment.

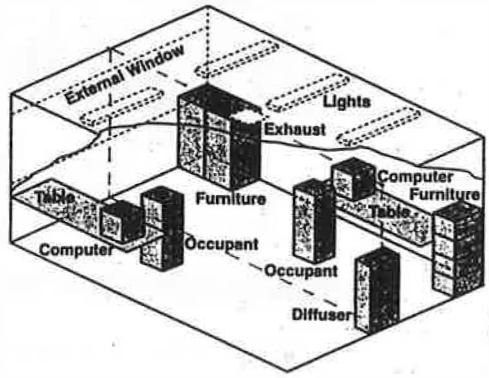


Figure 3. Space layout of a two-person office used in the experiment

A perforated displacement diffuser, 0.5 m wide and 1.1 m high, was placed at the middle of the right side wall near the floor. The effective area ratio is 10%. The exhaust, 0.43 m x 0.43 m, was placed at the center of the ceiling.

The occupants in the test room were simulated by two boxes, 0.4 m long, 0.35 m wide, and 1.1 m high, each heated by three 25 W light bulbs. The surface temperature was between 28 to 30 °C. As shown in Figure 5, two point sources of SF_6 were introduced at the top of the two boxes to simulate contaminants from the occupants, with an initial velocity of 0.045 m/s in the horizontal direction. Two real PCs were used to generate heat. One generated 108 W and the other 173 W. Six 34 W fluorescent lamps were used during the experiment as overhead lighting. In addition, two tables and two file cabinets were also in the room. The ventilation rate was 4 ach that corresponded to a face velocity of 0.09 m/s at the diffuser. The supply air temperature was controlled at 17 °C. The window surface temperature was 27.3 – 28.1 °C and the surface temperature on the movable wall was 24.2 to 26.6 °C. The surface temperatures on the other walls were 23.3 – 26 °C.

Five movable poles were placed in the test room and each supported six hot-sphere anemometers and six air sampling tubes. Additionally, two thermo-couples were also attached on each pole to measure air temperature near the floor and ceiling. A total of 40 thermo-couples were used to measure the surface temperature of the floor, ceiling, window, and walls.

Measurements were conducted under steady-state conditions by stabilizing the room thermal and fluid conditions for more than 12 hours before recording the data. Air velocity, air temperature, and SF_6 concentration were measured in nine different positions with a total of 54 measuring points for air velocity, 72 for air temperature, and 54 for tracer gas.

The measured air velocities can be used for determining turbulent intensity and the measured concentrations for local mean age of air. Since the omni-directional anemometers have a large uncertainty in measuring low air velocity, we feel the fluctuating velocity, |u'|, that is the sum of three components of the fluctuating velocity, i.e., $\sqrt{u_1'^2 + u_2'^2 + u_3'^2}$, could provide more accurate information than turbulent intensity.

This investigation has further used the step-up and decay method to determine the age of air, τ:

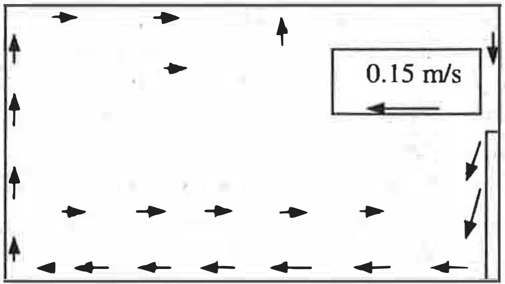
$$\tau = \int_0^\infty \left(1 - \frac{C(t) - C(0)}{C(\infty) - C(0)}\right)dt \quad \text{(step-up)} \quad (1)$$

$$\tau = \frac{\int_0^\infty C(t) - C(\infty)dt}{C(0) - C(\infty)} \quad \text{(decay)} \quad (2)$$

where C is the tracer-gas concentration.

RESULTS

Figure 4 shows the flow pattern, observed by using smoke, in the mid-section through the diffuser (the dashed line in Figure 3). The velocity determined from the smoke-visualization is rather reliable because the speed is low. Due to buoyancy, the cold air through the supply diffuser spreads on the floor level. This cold air flow is like a jet and induces the surrounding air. As a result, the induction causes a reverse flow in the layer between 0.5 to 1 m above the floor. The figure does not show the thermal plumes generated by occupants and computers, because they are in a different



section.

Figure 4. The observed airflow pattern by using smoke visualization (side view of the room). The length of the arrow is proportional to the velocity level.

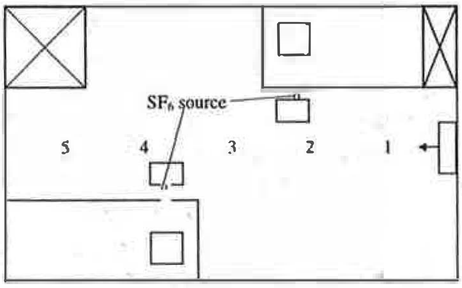


Figure 5. The measuring positions (top view of the room).

Figures 6 to 9 present, respectively, the measured temperature, SF_6 concentration, velocity, and velocity fluctuation in the five positions shown in Figure 5. The vertical axes are dimensionless elevation normalized by room height, and the horizontal axes are dimensionless measured parameters. These figures also show the computed results by CFD with an RNG k-ε model. The agreement

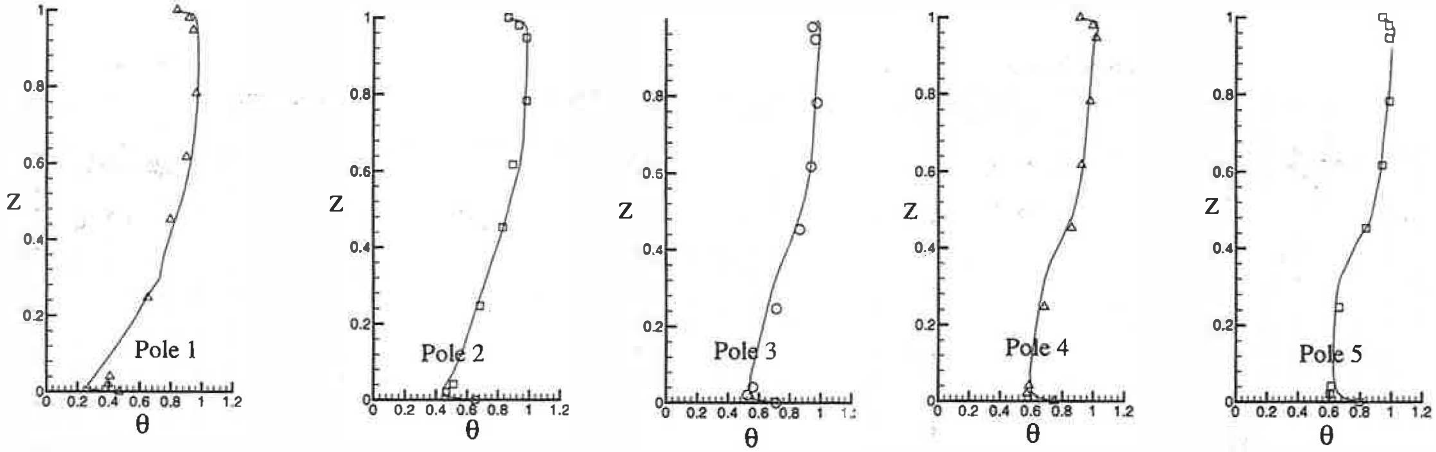


Figure 6. Temperature profiles in five positions of the room.
$\theta = (T - T_{in}) / (T_{out} - T_{in})$, $T_{in} = 17.0\ ^{o}C$, $T_{out} = 26.7\ ^{o}C$, z = height /room height, symbols – measured data, lines – computed results.

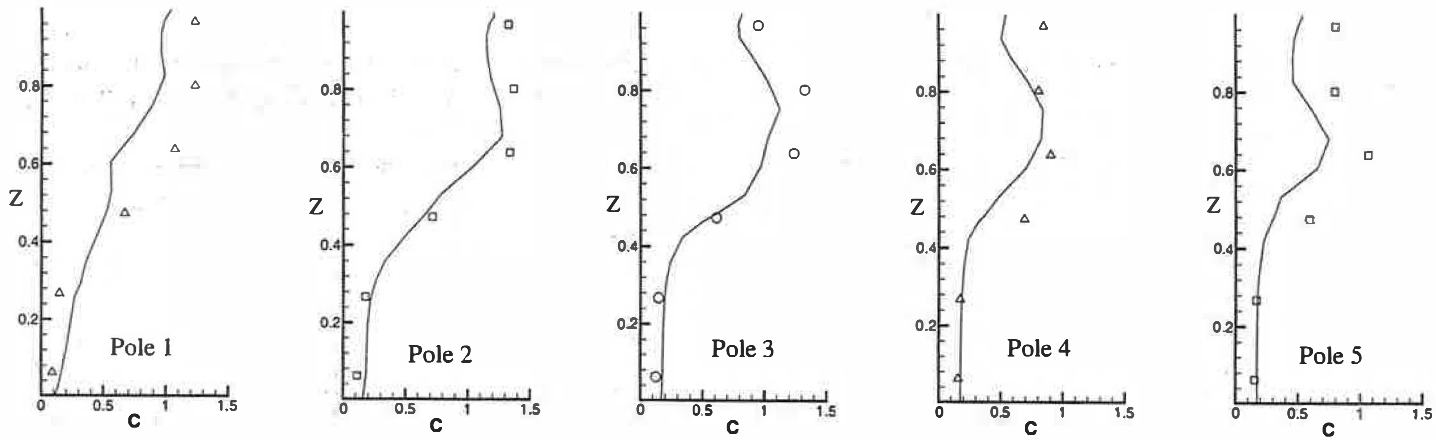


Figure 7. SF_6 concentration profiles in five positions of the room.
$c = (C - C_{in})/(C_{out} - C_{in})$, $C_{in} = 0$ ppm, $C_{out} = 0.421$ ppm, z = height /room height, symbols – measured data, lines – computed results.

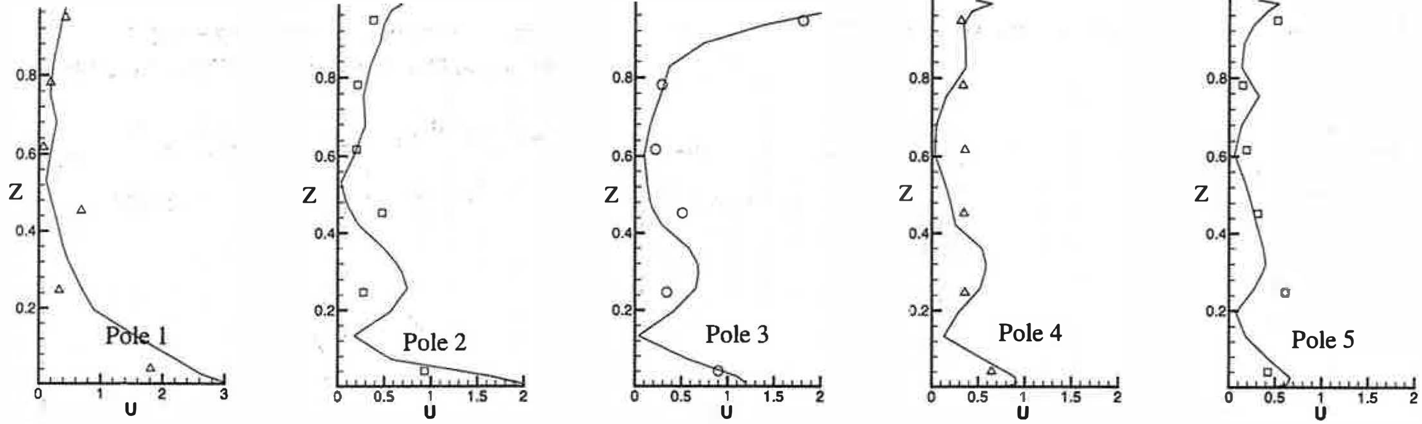


Figure 8. Mean velocity profiles in five positions of the room.
$U = u/u_{in}$, $u_{in} = 0.09$ m/s, z = height /room height, symbols – measured data, lines – computed results.

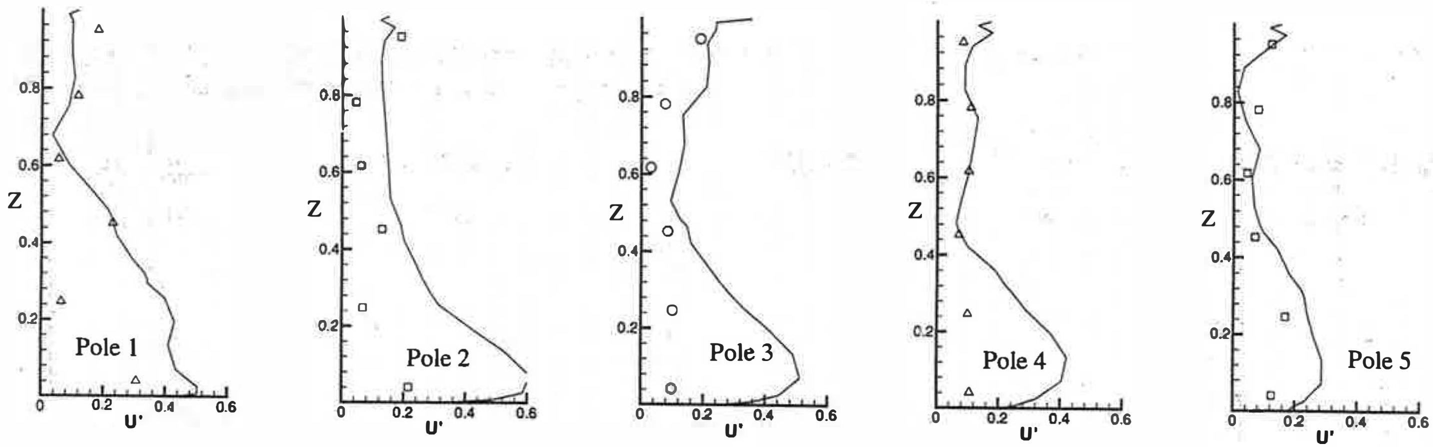


Figure 9. Velocity fluctuation profiles in five positions of the room.
$U' = u'/u_{in}$, $u_{in} = 0.09$ m/s, z = height /room height, symbols – measured data, lines – computed results.

between the computed results and measured data is generally good. More information about the CFD computations will be published in another paper.

Figure 6 clearly shows that the displacement ventilation system created temperature stratification. The temperature gradient in the lower part of the office is much larger than the one in the upper part, because most heat sources (occupants and computers) are located in the lower part of the room.

The SF_6 concentration in the upper zone is not uniform and very sensitive to the source position and thermal boundary conditions. The SF_6 concentration in the occupied zone is much lower than that in the upper zone as shown in Figure 7. The concentration increases rapidly between Z of 0.4 and 0.5, which can be considered as the stratification height. Since convective flow around the human body may bring the air at the lower level to the breathing level, the displacement ventilation provides better indoor air quality than mixing ventilation.

Figure 8 shows that the velocity in most of space, except near the floor, is lower than 0.05 m/s. The magnitude is so low that the hot-sphere anemometers may fail to give accurate results. Nevertheless, the measured velocity is close to that observed through the use of smoke.

The measured velocity fluctuation shown in Figure 9 is less reliable, because of the large probe size. In addition, the computed velocity fluctuation is $\sqrt{2k}$, where k is the turbulent kinetic energy. Furthermore, the turbulence model may not accurately calculate turbulent energy. Therefore, it is not surprising to see the large discrepancies between the computed profiles and measured data.

Figure 10 shows the transient CO_2 concentration at the middle of position 4 in Figure 5. From the measured data, we have calculated the age of air at this point to be 860 seconds.

Due to limited space available in the paper, the results presented here are not complete. We have prepared a separate report that details all the measured data and thermal and fluid boundary conditions. The report is available upon request.

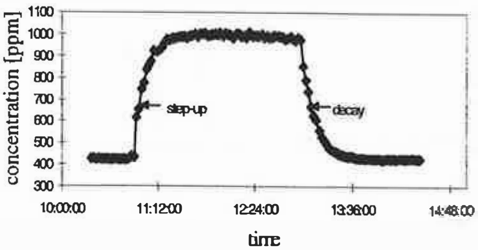


Figure 10. Transient CO_2 concentration profile for determining the age of air.

CONCLUSIONS

This paper presents the detailed flow data of displacement ventilation, gathered at the environment test facility at the Massachusetts Institute of Technology. The data include airflow patterns observed by using smoke and the distributions of air velocity, velocity fluctuation, temperature, and tracer-gas concentration. Detailed information of thermal and flow boundary conditions is also available. The data are useful for validating a CFD program for indoor environment design.

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