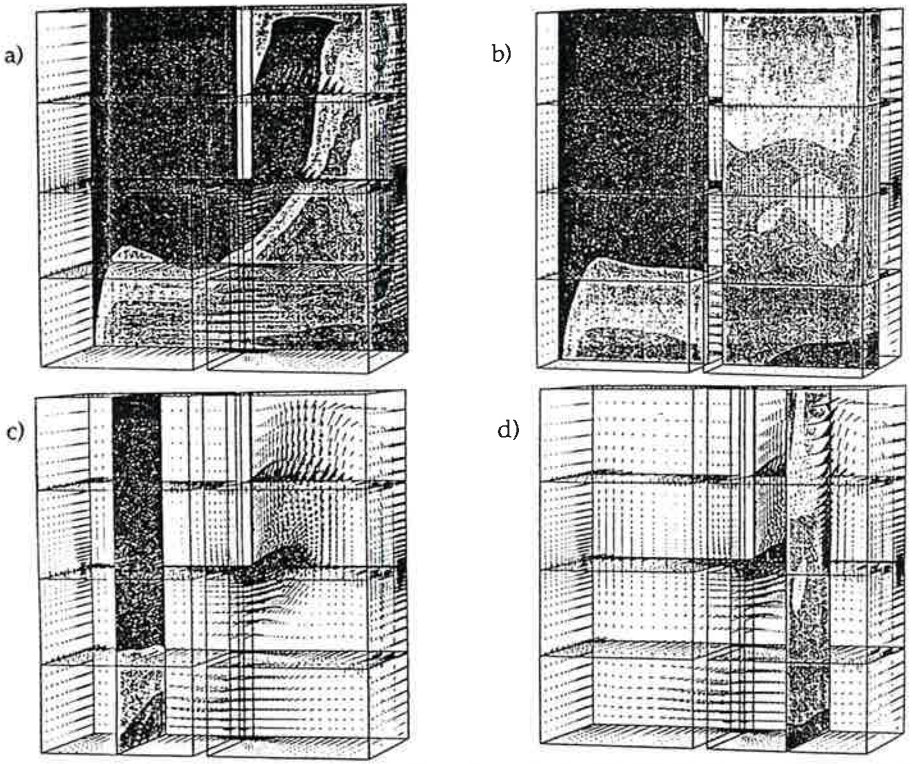

Figure 4. TWS^h simulation of partitioned-room geometry of [6], Ra=10^6, velocity and temperature distributions on symmetry- (a) and select (b-d) quarter-planes.

SUMMARY AND CONCLUSIONS

A FE spatial semi-discretization of a Taylor weak statement forms the theoretical basis for a new CFD algorithm, for application to prediction of thermal room air motion. The formulation ingredient of stability, without excess artificial diffusion, is validated for a benchmark. A three-dimensional solution is discussed for a natural convection, two-partition room geometry.

ACKNOWLEDGMENTS

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AIR FLOW PATTERN AND POLLUTANT TRANSMISSION IN AUDITORIA - MEASUREMENTS AND CFD-SIMULATIONS

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ABSTRACT

This paper deals with air flow pattern and pollutant transmission in auditoria. Through different tracer gas techniques the air distribution and the removal of contaminants inside auditoria have been classified in terms of air exchange efficiency, local air change index, ventilation effectiveness and local ventilation index. Situations with various occupancy and ventilation rate have been studied.

The tracer gas measurements were supplemented and generalized by numerical simulations carried out with the CFD code KAMELEON. The simulations have shown that the air flow pattern inside this type of premises may be quite complex. The air flow pattern is affected by room geometry, capacity and location of heat source, aspects of building materials and construction, furnishing, the ventilation principle, supply air temperature and surrounding climate.

A general trend from simulations of terraced premises is that the upper part of the occupied zone appears to be the most polluted area with regard to both thermal and atmospherical contaminants. This tendency is independent of the ventilation principle and technical layout.

INTRODUCTION

The air flow pattern within a zone can have a considerable impact on the indoor air quality, the thermal comfort and the energy performance of the ventilation system. Studies in auditoria, carried out by the author, have shown that the air flow pattern and the pollutant transmission are affected by many parameters. These include room geometry, capacity and location of heat source, building fabrics, furnishing, ventilation principle, leakages and short circuiting, supply air temperature and surrounding climate.

Even with a sophisticated measuring concept, it is difficult to consider in detail the pattern of the air flow, or the influence from air movement on thermal and pollutant transport. Computational fluid dynamics (CFD) enables the air flow pattern to be predicted within a zone with a wealth of details, if sufficient computer resources are available.

The objective of this work has been to verify and visualize the impact of parameters affecting the air flow pattern inside auditoria with terraced floor. The work was accomplished by carrying out full scale measurements and CFD computations of the air flow pattern and pollutant transmission.

METHODS

Air flow patterns and pollutant transmission inside two auditoria were studied by use of tracer gas technique. One auditoria was ventilated by displacement (EL5) the other was ventilated by dilution (F1). Pollutant distribution, ventilation effectiveness, local ventilation index and temperature profiles were measured and related to occupancy. Fig. 1 shows the data acquisition system handling the full scale measurement in auditorium EL5. Three measurement columns (c1..c3) containing 19 spots for gas, thermocouple and humidity covered the situation inside the room. In addition measurement spots were located inside the ventilation plant.

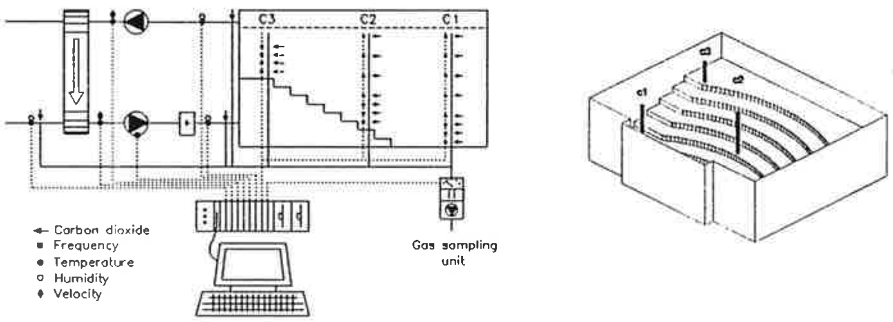

Fig. 1. Data acquisition system, sensor arrangement and location of measurement columns.

The results from the full scale trials were supplemented and generalized by numerical analysis. The numerical analysis was carried out with the CFD code KAMELEON. The CFD simulations involved studies of various room geometries, ventilation principles and ventilation layouts. The auditoria were modelled in three dimensions, using a non-uniform ortogonal grid system. Figure 2 shows a graphical representation of the model.

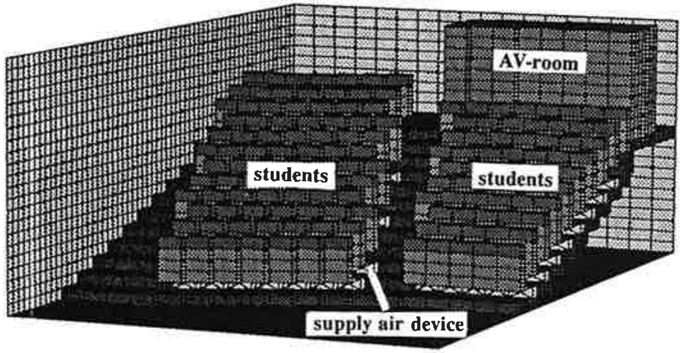

Fig. 2. Graphical representation of the CFD model - EL5
The auditorium is fully occupied

Only half of the room was modelled, presuming that the other half represent a symmetric reflection. The model was subdivided into 29184 control volumes. Each volume was sized to 24*25*50 cm. All surfaces were modelled as isothermal boundaries. Initial surface temperature and heat load were gathered from the full scale trial.

RESULTS

The F1 auditorium is in the Physics Department at the Norwegian Institute of Technology (NTH). The building construction is concrete. Inside the walls are covered by wooden panelling. The auditorium has a seating capacity of 500 students. The ventilation principle is based on dilution with diffusors in the ceiling and exhaust devices under the seats at the front of the auditorium. The measurements were carried out in spring 84, as a part of the project "Ventilation by Demand" /1/. During the experiments, the carbon dioxide concentration was measured in the supply, the exhaust and inside the room. Totally six gas spots were recorded. Figure 3 shows an example of the carbon dioxide concentration as a function of variable occupancy during a day.

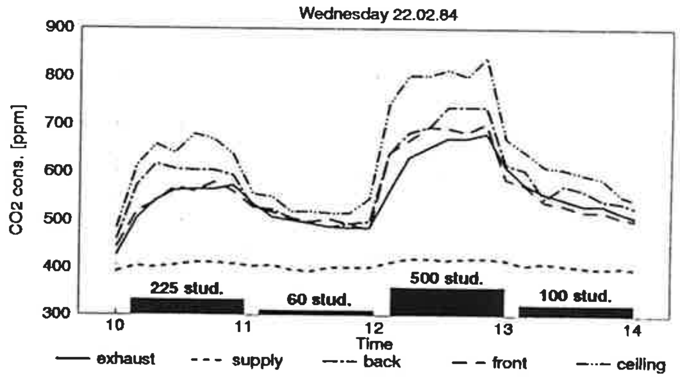

Fig. 3. Carbon dioxide concentration in auditorium F1.

As we can see from Figure 3, the concentration inside the auditorium is inhomogeneous, and the lowest concentration is recorded in the exhaust. This indicates that there is a short circuiting between the supply and exhaust. Calculations of ventilation effectiveness have revealed that the short circuiting is occupant load depended. The calculated effectiveness for some situation is given in Table 3.1.

Table 1. Calculated effectiveness $<\epsilon_v>$

Occupant load	Ventilation effectiveness
50	0.98
120	0.74
180	0.68

Complete mixing ($<\epsilon_v> = 1.0$) was only achieved when the auditorium was empty.

CFD simulations of pollutant transmission and air flow pattern in F1 has shown result almost identical to the experience gained from the full scale trials. CFD results from a fully occupied auditorium identical to auditorium F1 is shown in Figure 4. In addition a second simulation with exhaust slots repositioned at the back of the auditorium was carried out. An auditorium with supply air injected as jets via nozzles in the ceiling, and exhaust slots equally dispersed all over the floor was also simulated.

Efficient elimination of contaminants by dilution, presumes a well mixed air flow pattern. The measurements and simulations have indicated that densely occupied premises generate strong thermal convection flows, which complicate the mixing. The result is short circuiting between the supply and exhaust.

Arrangement with diffusors in the ceiling and exhaust slots at the back shows that the environment is somewhat improved compared to a similar system with exhaust slots at front (F1). Even the system with supply air injected as jets from the ceiling did not manage to establish uniform conditions inside the room.

Auditorium EL5 is located at the Department of Electrical Engineering and Computer Science at the Norwegian Institute of Technology. The auditorium has a seating capacity for 300 students. The walls are made of light concrete. Floor, furnishing and intermediate ceiling are made of wood. The auditorium is ventilated by displacement with inlet devices under the seats and exhaust slots in the intermediate ceiling. The measurements were carried out during the winter 90/91.

The air distribution inside the auditorium was examined by combining three different load situation with two different flow rates. Table 2 shows the air exchange efficiency as a function of occupancy and ventilation rate.

Table 2. Air change efficiency (ϵ_a)

Ventilation rate supply/exhaust	6.850/5.606 m^3/h			12.125/10.629 m^3/h		
No. of occupants	0	130	220	0	150	240
ϵ_a	0.63	0.65	0.63	0.62	0.59	0.59

The results tell us that the air distribution in the auditorium takes place by displacement ($\epsilon_a > 0.5$). Further we can read that the air change efficiency within the tested ranges, is little affected by the variation of air flow and occupancy. Measurements of local air changes indicate that when the room is fully occupied, the air distribution to the middle of room is some what better then the air distribution to the corners. This is also confirmed by measurements of local ventilation indexes.

CFD simulations of auditorium EL5 have confirmed a reasonable conformity between measurements and simulations. Figure 4 shows a situation from a partly occupied auditorium with dispersed seating pattern.

CFD simulations carried out for auditorium EL5 included studies of air flow pattern and pollutant transmission related to seating pattern, location of air terminal devices and room design/geometry. The simulations have shown that in premises with terraced floor,

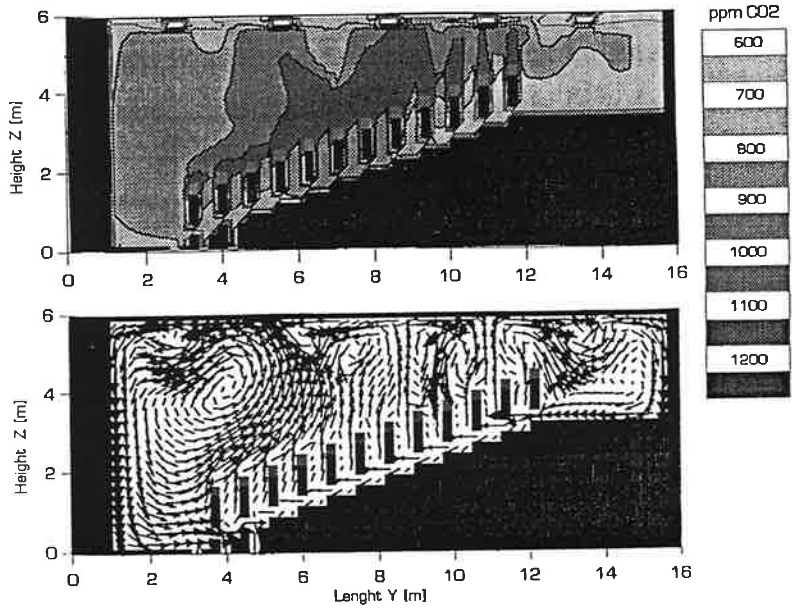

Fig.4 Concentration chart and air flow pattern - auditorium F1
Diffusors in the ceiling, exhaust slots at the front
Occupancy : 300, Airflow : 10,000 m^3/h

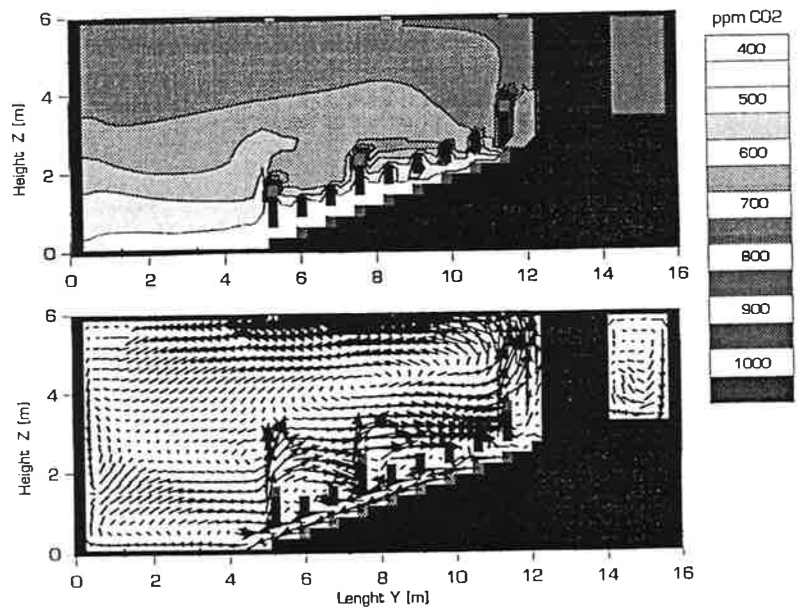

Fig.5 Concentration chart and air flow pattern - auditorium EL5
Auditorium partly occupied, dispersed seating patter
Occupancy : 100, airflow : 10,000 m^3/h, displacement ventilation

location of air terminal devices has a small influence on the air flow pattern. The seating pattern however, has a significant influence. The simulations have also shown that minor building details may have a considerable influence on the air flow pattern.

DISCUSSION

The study has shown that the temperature and pollutant distribution predicted by the CFD simulations corresponded reasonably with the full scale measurements. A general trend for terraced auditoria is that the upper part of the occupied zone appears to be the most polluted area. This tendency is independent of ventilation principle and location of air terminal devices. The study has also shown that there is a large risk of occupancy dependent short circuiting between supply and exhaust devices in terraced auditoria ventilated by dilution.

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VENTILATION EFFECTIVENESS MEASUREMENTS IN TWO MODERN OFFICE BUILDINGS

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ABSTRACT

Ventilation effectiveness measurements were made in two office buildings employing the age-of-air approach. The objective of these tests was to study the applicability of the associated tracer gas procedures in mechanically ventilated office buildings. Experimental issues were investigated including the ability to establish a uniform tracer concentration at the start of the test and the relationship of ventilation system configuration and system operation on the test procedure. The test results indicate good mixing of the ventilation air within the occupied space. In addition, experience was obtained with the measurement procedures that will assist the development of a standardized approach to measuring ventilation effectiveness in the field.

INTRODUCTION

Ventilation systems are designed to provide adequate amounts of outdoor air, to distribute this outdoor air throughout the occupied space, and to maintain thermal comfort. There are numerous design features and performance parameters relevant to these goals. Ventilation effectiveness has been described in general terms as the ability of a ventilation system to meet its design objectives (1). Specific definitions of ventilation effectiveness also exist that address air mixing within ventilated spaces. These definitions are based on concerns that significant quantities of supply air may be flowing directly into the return or exhaust without reaching the occupied space, so-called "short-circuiting." In such situations, appropriate amounts of outdoor air may not be delivered to the occupied portions of the space and internally-generated contaminants may build up to undesirable levels.

The ability to evaluate the existence of short-circuiting in the field and to assess the performance of innovative approaches to air distribution is limited by a lack of validated measurement procedures to assess ventilation effectiveness. A variety of procedures have been suggested, and some laboratory and field applications of these procedures have been conducted. Of these various procedures, the age-of-air approach is one of the more promising for use in the field (2-4). The ventilation effectiveness measurements conducted to date in U.S. office buildings using the age-of-air approach indicate good mixing of the ventilation air within ventilated spaces (5,6). While these measurements have not identified serious problems of short-circuiting, they have noted problems of air distribution on larger scales within buildings. For example, situations have been encountered in these and other studies in which whole floors or other large areas within buildings do not receive appropriate proportions of supply and outdoor air.

This paper describes ventilation effectiveness measurements based on the age-of-air approach and tracer gas decay techniques in two mechanically ventilated office buildings. A detailed description of these tests and the results is contained in reference (7). These tests were conducted in order to investigate the applicability of these measurement techniques in the field.

Because these procedures have had only limited use in the field, many questions remain regarding procedures to establish initial conditions, the effects of envelope infiltration and ventilation system operation, data interpretation and the level of accuracy achievable in the field.

BUILDING AND VENTILATION SYSTEM DESCRIPTIONS

The first building is located in Overland, MO, about 2.5 km (4 miles) west of St. Louis, and consists of seven floors, five above grade and two below. The building has a total floor area of about 35,100 m^2 and a volume of about 129,000 m^3. A detailed description of the building, including floor plans and air handler schematics, is contained in reference (8). The HVAC system is a variable air volume (VAV) system that utilizes unpowered VAV units in the interior zones of the building and fan powered units in the perimeter zones. The building ventilation system is zoned horizontally with two air handling systems on each floor serving the east and west sides of the building. A separate air handling system serves an atrium.

The second building, located in Portland, OR, is a seven story office building with a one story basement and a two story underground parking garage. The conditioned office space within the building has a floor area of approximately 34,600 m^2 and a volume of 134,000 m^3. A detailed description of the building, with floor plans and air handler schematics, is contained in reference (9). A penthouse mechanical room houses the main HVAC systems, consisting of three large, dual-duct VAV air handling systems, one serving seven floors of the center of the building and the others serving the east and west sides.

VENTILATION EFFECTIVENESS MEASUREMENT PROCEDURES

The ventilation effectiveness measurements in these two buildings employed the tracer gas decay technique to determine the age of air (2-4). The average age of air at a location is defined as the average amount of time that has elapsed since the air molecules at that location entered the building. The local age of air at a point is denoted by τ_i, and the local age of air averaged over a particular space is denoted by $\langle\tau\rangle$. The inverse of the building air change rate is referred to as the nominal time constant of the building τ_n. The local air change effectiveness ε_i characterizes the ventilation effectiveness at a specific location and is defined as

$$\varepsilon_i = \tau_n/\tau_i. \qquad (1)$$

The mean air change effectiveness of a building or a space η is a measure of the overall air distribution pattern for the building or space and is given by

$$\eta = \tau_n/\langle\tau\rangle. \qquad (2)$$

If the air within a space is perfectly mixed, then the local age of air τ_i will be the same throughout the space and equal to τ_n. The value of $\langle\tau\rangle$ will also equal τ_n. The local air change effectiveness ε_i at all locations within the space and the mean air change effectiveness η for the space will equal one. In the idealized case of pure piston flow through the space, τ_i will be minimized near the supply and maximized near the return. The mean age of air for the space $\langle\tau\rangle$ will equal $\tau_n/2$, and therefore η will equal 2, its maximum value. The local air change effectiveness ε_i will be below one near the return and above one near the supply. If there is non-uniform air distribution within a space, those locations with poor ventilation air distribution will have local ages of air that are higher than the space average. Locations in the so-called "stagnant" regions will have values of τ_i that are relatively large and values of ε_i significantly less than one, a generally undesirable situation. With significant stagnation in a space, the value of η for the space will be below one.

The measurements in both buildings employed an automated tracer gas measurement system that has been used previously to provide continuous measurements of building air change rates and employs sulfur hexafluoride (SF_6) as the tracer gas. The system controls tracer gas injection and air sampling, records SF_6 concentrations, and monitors and records outdoor weather, indoor temperature and fan operation status. The installation of these systems in the Overland and Portland buildings are described in references (8) and (9).

In conducting age-of-air measurements with the tracer gas decay technique, tracer gas is injected into the building in order to achieve the required initial conditions of a uniform tracer gas concentration throughout the building. The tracer gas injection locations are based on the layout of the building and its ventilation systems. One approach is to inject tracer gas at a constant rate into the building air handlers until equilibrium conditions have been achieved. During the injection, some adjustment of the injection flow rates will be required so that all portions of the building attain the same equilibrium concentration. Depending on the building, it may take 8 hours or more to reach a uniform concentration, and the degree of uniformity achievable in a given building may be limited.

Once a uniform tracer gas concentration is attained in the building, the tracer gas injection is stopped and the tracer gas concentration decay is monitored at selected points in the building. The age of air at a given location is determined from the following equation:

$$\tau_i = \frac{1}{C_{i,0}}\int_0^\infty C_i(t)\,dt \qquad (3)$$

where $C_i(t)$ is the tracer gas concentration at time t and $C_{i,0}$ is the concentration at t=0. In these tests, this integral was evaluated based on numerical integration of the concentrations measured at 10 minute intervals using the automated tracer gas monitoring system. The nominal time constant τ_n for the building was determined based on the tracer gas concentration in the building just before the tracer gas injection was stopped, as given by the following formula:

$$\tau_n = \frac{C_{eq}\,V}{q} \qquad (4)$$

where C_{eq} is the building average of the equilibrium tracer gas concentration, V is the building volume and q is the tracer gas injection rate.

RESULTS

This section presents a summary of the results of the measurements in the two buildings. Five tests were conducted in the Overland building, and four were conducted in Portland. In the first two Overland tests, the decay was monitored in the same 15 return airstreams that were monitored during the injection. In these tests, the age of air in these returns were measured as an indication of the differences in the outdoor air delivery rates to the 15 building zones. In the others tests, the age-of-air measurements focused on either the west or east sides of the building. In these tests, the age of air was measured in the return airstreams on the designated side of the building and in selected locations in the occupied space at a height of about 1.5 m (5 ft) above the floor. In the four Portland tests, the age of air was measured in each of the three return airstreams (central, east and west) and about 15 locations within the occupied space.

Example of Test Results

While there is not sufficient space to present all of the test results, Table 1 contains an example of the results for one of the Portland tests. The first column of the table contains the location of the measurement, with the results presented in three groups based on the three zones in the building. Return fans #6, #7 and #8 correspond to the center, east and west portions of the building respectively. The occupied space locations in each group are in the zones served by the designated return fan. The column numbers used to identify the measurement locations refer to floor plans contained in reference (9). The second column of these tables contains the initial tracer gas concentration $C_{i,0}$ at each location. The next two columns contain the age of air at each location, with values obtained in the return airstreams designated as τ_r and values obtained in the occupied space designated as τ_i. The last two columns contain the air change effectiveness. For the return airstreams, the air change effectiveness is defined as the nominal time constant of the building τ_n divided by age of air in the corresponding return airstream τ_r. For the occupied space locations, the air change effectiveness is defined as the age of air in the corresponding return airstream τ_r divided by τ_i. The value of τ_n is given at the bottom of the table. The location marked with the symbol * has a value of $C_{i,0}$ that is more than 20% different from the mean value of the equilibrium concentration in the building returns.

Table 1. Results of Portland Test B

Location	$C_{i,0}$ (ppb)	Age of Air (hours)		Air Change Effectiveness	
		Return, τ_r	Space, τ_i	τ_n/τ_r	τ_r/τ_i
Return fan #6	79	2.13	--	0.89	--
7th floor, column Q14	73	--	2.06	--	1.03
6th floor, column Q14	78	--	2.11	--	1.01
5th floor, column Q14	67	--	2.32	--	0.92
4th floor, column Q14	79	--	2.08	--	1.02
3rd floor, column Q14	69	--	2.23	--	0.96
2nd floor, column Q14	79	--	2.10	--	1.01
1st floor, column Q14	70	--	2.24	--	0.95
Return fan #7	70	2.25	--	0.84	--
7th floor, column M22	70	--	2.25	--	1.00
5th floor, column M22	73	--	2.24	--	1.00
3rd floor, column M22	64	--	2.41	--	0.93
1st floor, column M22	80	--	2.07	--	1.09
Return fan #8	67	2.35	--	0.81	--
*7th floor, column V4	90	--	1.77	--	1.33
5th floor, column V4	77	--	2.10	--	1.12
3rd floor, column V4	70	--	2.17	--	1.08
1st floor, column V4	75	--	2.29	--	1.03

τ_n = 1.90 hours

Initial Conditions

These measurements require initial conditions of a uniform tracer gas concentration throughout the building. In the Overland tests, it was necessary to control and adjust 15 tracer gas injection rates in order to achieve a uniform tracer gas concentration. The standard deviation of $C_{i,0}$ for the fifteen return airstreams was 10% and 19% of the mean value for the first and second tests respectively. The uniformity of $C_{i,0}$ among the returns for the other three tests in Overland was about 10%. The values of $C_{i,0}$ at the occupied space locations exhibited more variation than the returns. Because the Portland building has three central air handlers that serve all seven floors of the building, and because the central, east and west zones communicate freely on the floors, it was much easier to achieve a uniform tracer gas concentration in this building than in Overland. There were few locations within the occupied space that deviated significantly from the average equilibrium concentration in the return ducts. Locations with a values of $C_{i,0}$ that were more that 20% different from the mean value of the equilibrium concentration in the building were considered separately in the analysis. At most one such location existed in each of the Portland tests, while 3 or 4 occurred in the Overland tests.

Air Change Effectiveness Values

Table 2 summarizes the air change effectiveness measurements at the occupied space locations in the two buildings. For each test the mean and standard deviation of the air change effectiveness is given for all of the occupied space locations and for those locations with values of $C_{i,0}$ within 20% of the mean value of $C_{i,0}$. The air change effectiveness presented here is based on the age of air measured in the return duct serving that location rather than the nominal time constant of the building. The return age of air was used rather than the nominal time constant because of variations in the outdoor airflow rates to the various building zones. If the air change effectiveness at a location was determined using τ_n as the reference, then the air change effectiveness values would have covered a much wider range and may have been misinterpreted. When local age of air is compared with the nominal time constant, the resultant air change effectiveness combines the effect of nonuniform outdoor air distribution to the different zones of the building and the effects of ventilation air mixing within the ventilated space. While both effects are important, one needs to look at them separately in order to evaluate and understand ventilation system performance in terms of air distribution.

Table 2. Summary of Air Change Effectiveness Test Results

Test	Air Change Effectiveness All Occupied Space Locations		Air Change Effectiveness Locations with $C_{i,0}$ within 20% of Mean	
	Mean	Standard Deviation	Mean	Standard Deviation
Overland				
Test C	1.11	0.25	1.03	0.10
Test D	1.19	0.17	1.24	0.17
Test E	1.03	0.13	1.00	0.07
Portland				
Test A	0.93	0.10	--	--
Test B	1.03	0.10	1.01	0.06
Test C	1.00	0.14	0.97	0.11
Test D	1.05	0.11	1.07	0.17

The values of the air change effectiveness are generally close to 1.0, the value for conditions of perfect mixing of the ventilation air. Given the limited amount of field testing that has been performed to date, it is not yet possible to reliably estimate measurement errors and to state how large of a deviation from 1.0 is significant. Based on existing experience, measurement errors are thought to be no smaller than 10% (5, 6). Neglecting the measurements for which $C_{i,0}$ was more than 20% from the building average had little effect on the mean value of the air change effectiveness, but generally reduced the standard deviation.

SUMMARY AND DISCUSSION

The measurements of ventilation effectiveness in the Overland and Portland buildings serve as a field demonstration of age of air measurement procedures. They have provided additional experience with the measurement procedures and additional building performance data. Several important issues were addressed that need to be understood in developing a standardized measurement procedure.

In using the tracer gas decay technique, the ability to achieve a uniform tracer gas concentration is critical. In these tests, the equilibrium tracer gas concentration was generally within 10% of location of air terminal devices has a small influence on the air flow pattern. The seating pattern however, has a significant influence. The simulations have also shown that minor building details may have a considerable influence on the air flow pattern.

DISCUSSION

The study has shown that the temperature and pollutant distribution predicted by the CFD simulations corresponded reasonably with the full scale measurements. A general trend for terraced auditoria is that the upper part of the occupied zone appears to be the most polluted area. This tendency is independent of ventilation principle and location of air terminal devices. The study has also shown that there is a large risk of occupancy dependent short circuiting between supply and exhaust devices in terraced auditoria ventilated by dilution.

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