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Measurements of the Age of Air and Ventilation Efficiency in an Auditorium

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The age of the air was measured at several locations in the auditorium D16.2 of the ETH Zurich, as well as the air flows in the ventilation system. This paper presents the measurement techniques and the results of these measurements. It results that the air is well mixed in the auditorium itself, but that a short-cut in the ventilation system reduces its efficiency.

1. Introduction

1.1. Scope of the presentation

To ensure health, safety and comfort in buildings, an efficient ventilation strategy should provide an adequate supply of fresh air to the building occupants. Since it can be assumed that the older the air is, the greater is its contaminate concentration, knowledge of the residence time or age of air is of great importance. From these quantities, various associated expressions of efficiency or effectiveness can be calculated.

The measurement of the local mean age of air at various locations in a room is useful to verify the efficiency of the ventilation system and to assess the main air streams and the dead zones. Several methods, using tracer gas, can be used to measure the age of air. The scope of this contribution is to present the basic concepts and an example of application.

1.2. Basic definitions and concepts

The **age of a particle of air** within a room is defined as the elapsed time since the particle entered the room or the ventilation system, as if that particle were born when entering the room. Since several particles, having different ages, arrive at a given location, is is useful to define the **local mean age of air** at a point $\underline{r}$, $\bar{\tau}_r$ which is the average age of all the air particles arriving at that point. Finally, the **room mean age of air** $<\tau>$ is defined by the average of the local mean ages of the air particles in the room.

The **nominal time constant**, τ_n, of the room is the time obtained by dividing the volume of the room [m³] by the volume flow rate of the fresh air [m³/h]. This time constant is the inverse of the specific air flow rate or air change rate.

An efficient ventilation system is a system which changes quickly the air of the room with a minimum amount of energy, that is by moving as few air as possible. It is shown [4], that the time required to change the air in a room is twice the room mean age. Therefore, a **air change efficiency** can be defined by [6]:

$$\eta_a = \frac{\tau_n}{2\langle\tau\rangle}$$

The best efficiency can be realized by a displacement ventilation system, in which the fresh air pushes the old air like a piston. In this case, the room mean age is half the nominal time constant, and the air change efficiency is 1 (or 100 %).

In case of complete mixing, the room mean age is equal to the nominal time constant, and the air change efficiency is 0,5 (or 50 %). If there are dead zones in the room, this efficiency can even be worse, since, for a given nominal time constant, the room mean age may grow without limit.

1.3 Measurement methods for the age of air

The basic principle is to mark the air to be traced with a gas (the tracer gas), according a known schedule, and to follow the concentration of that tracer gas at the location of interest. This technique is based on the assumption that the tracer gas behaves the same as the air: no adsorption, same buoyancy. It can be readily understood that if the air is marked at the inlet by a short pulse of tracer gas, and if the tracer molecules follow the air molecules, they will arrive at a given location at the same time as the air molecules (Figure 1).

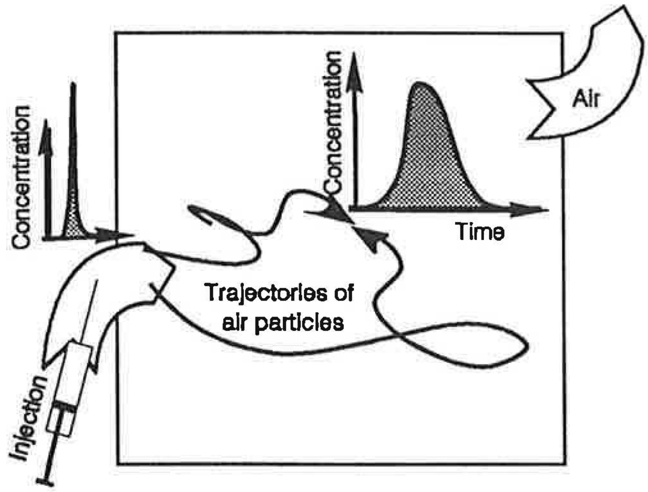

Figure 1: Illustration of the pulse technique to measure the local age of air

In fact, the pulse technique is not the only one and the local mean ages can be measured by recording the time history of the net tracer concentration, at any point, by either of three strategies as follows:

- **step down**: uniform concentration of tracer is achieved at the beginning of the test, when the injection is stopped,
- **step-up**: the tracer is injected at air inlet, at a constant rate from the starting time throughout the test,
- **pulse**: a short pulse of tracer is released in the air inlet at the starting time.

Figure 2 shows the variation of concentration during step-up and step-down measurements, while Figure 3 shows it for pulse measurement. These are measurements performed in the auditorium.

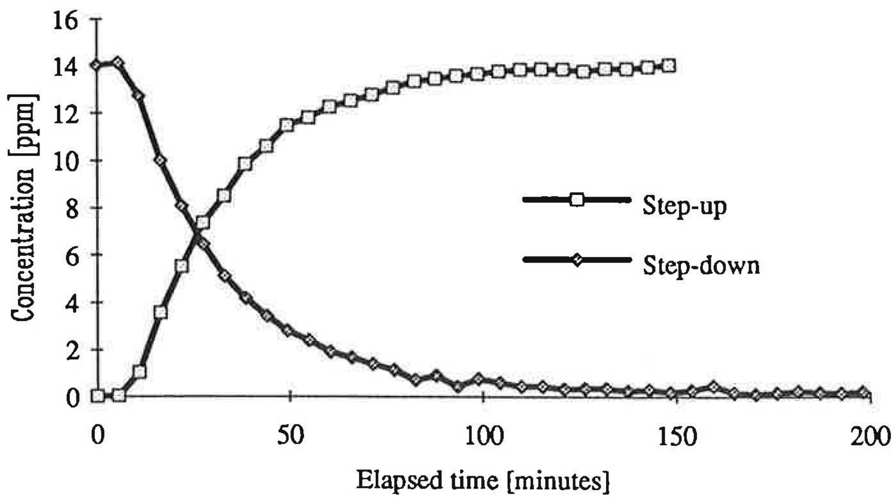

Figure 2: Variation of the concentration with time during measurements of the age of air, using step-up and step-down measurement techniques.

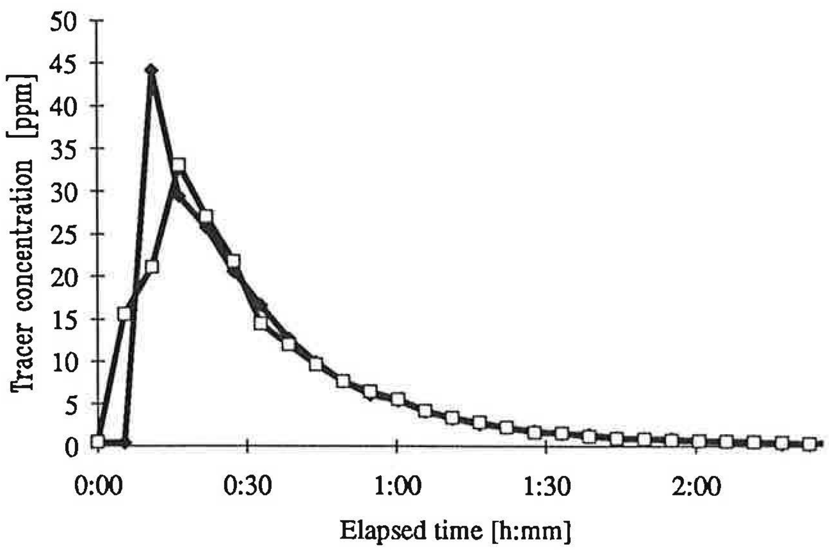

Figure 3: Concentration versus time during measurements of the age of air at two different locations, when using the pulse injection technique.

To interpret the recorded tracer gas concentrations and obtain the age of air, the background (or supply) concentration should first be subtracted from all measurements, and time should begin from start of the test (i.e. elapsed time) by subtracting the starting time from all time values. Finally, the concentration is normalized by dividing it either by the start concentration (step-down method), or by the final, equilibrium concentration (step-up technique) or by the integral of the concentration (pulse method). The local mean age at a given measurement location is finally obtained by numerical integration of these normalized concentrations [4, 5].

The room mean age can be obtained either by averaging the local mean ages measured at enough representative locations, or, for rooms with a single air exhaust, by measuring the variations of the concentrations in the exhaust duct, and interpreting the variations of the concentration according an adequate procedure [5].

Measurements

The Auditorium and its Ventilation System

The measured auditorium is room D 16.2 at the ETH Zürich. It has a volume of 440 m^3, and its own ventilation system, which pulses the air in the desks and in a row in the ceiling. Extraction grilles are in the ceiling, as shown in the cross section in Figure 4.

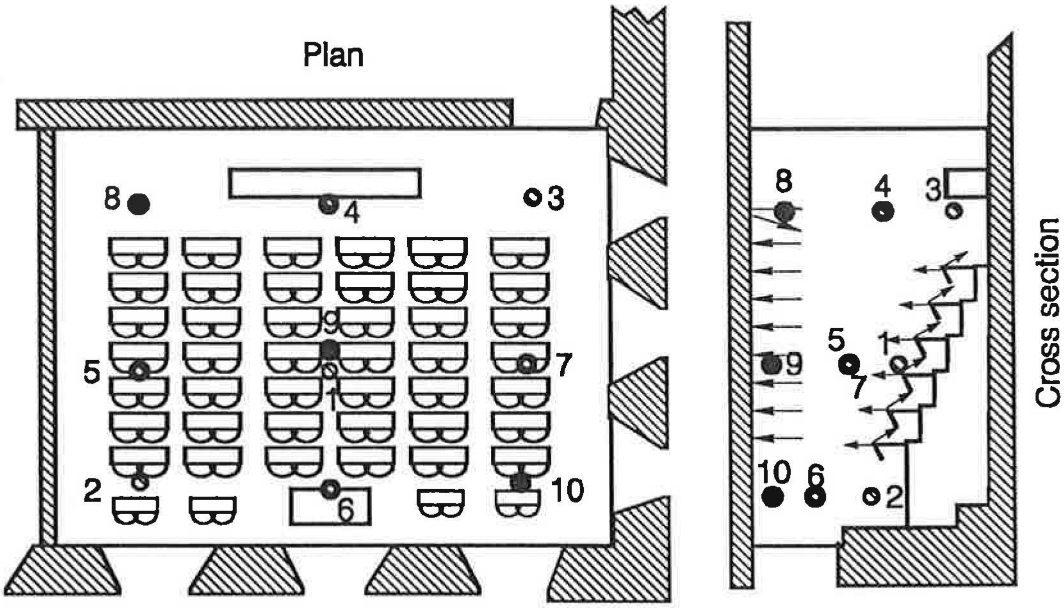

Figure 4: Plan and elevation of the auditorium, together with the locations of measurement. Arrows in the cross section show the air inlet and outlets.

The ventilation system is shown on Figure 5. It is a balanced system with a wheel heat exchanger between exhaust air and fresh air.

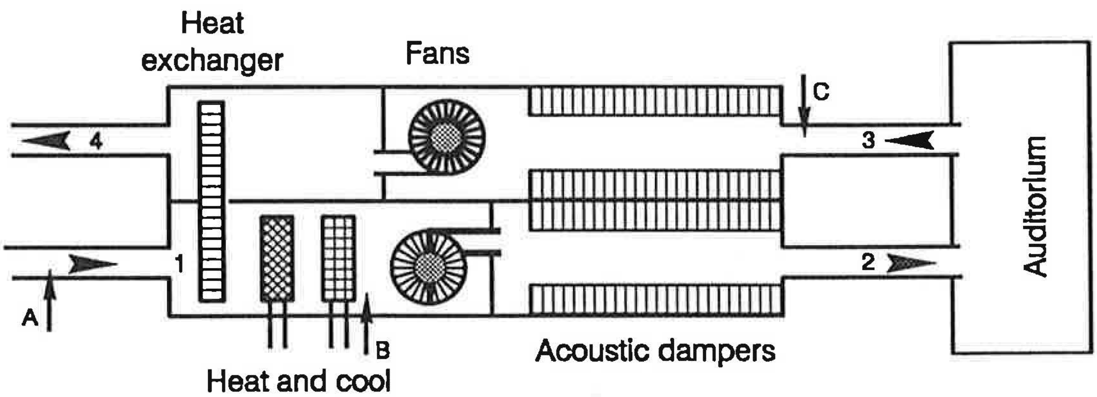

Figure 5: The ventilation system of the auditorium. A, B, and C are locations of injection of the tracer gas and points 1 to 4 are sampling points.

Measurements on the ventilation system

Three tracers were injected at a constant flow rate at three locations in the ventilation system: A) in the fresh air duct, upwind the heat exchanger; B) downwind the heat exchanger and C) in the exhaust duct, downwind the auditorium but upwind the exhaust fan. Samples of air were analyzed at locations 1 to 4 shown in Figure 5. Using the equations of conservation of air and of the three tracers, enough equations can be drawn and solved to obtain all the air flow rates occurring in the ventilation system *[1, 5]*. These are shown in Figure 6, the fans being set at low speed, which is the most frequent setting.

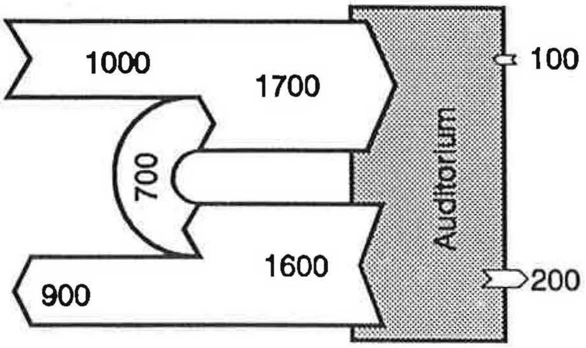

Figure 6: Air flow rates [m³/h] as measured in the ventilation system of the Auditorium, at low fan speed.

The main conclusion of this measurement is that there is an important and unexpected short cut which mixes a fraction of the exhaust air with the fresh air. The air flow rate entering the auditorium is close to the planned value, i.e. 1700 m3/h, but the real fresh air flow rate is much lower, that is 1000 m^3/h.

Since an important issue for a ventilation system is to bring fresh air in the ventilated space, an efficiency of the ventilation system, η_s, could be defined by the ratio of the fresh air flow rate delivered by the ventilation system to the total air flow rate going through the ventilated volume. In this case, this efficiency is:

$$\eta_s = \frac{1000}{100 + 1700} = 0.56 \text{ or } 56\ \%$$

Measurements in the Auditorium

The age of the air was measured at 11 locations in the auditorium, according an experimental plan already described *[1, 2]*. This experimental plan, which is the location of 10 of the measure points, is designed to provide a second degree mapping with the best possible accuracy. The age was measured using simultaneously two tracers and various techniques (pulse, step-up and decay) in order to compare the advantages and disadvantages of these techniques. This comparison will be presented elsewhere *[3]*, but this paper presents the results of these measurements, and their consequences with regard to demand controlled ventilation.

The measured locations in the first series of measurements are shown on Figure 4. Location 11 is in the exhaust duct, at about 10 m downwind of the exhaust grilles. The results of the measurements are shown on Table 1. The ventilation system was set at low speed, as it is set usually. Some comments on this table are given below.

The line number corresponds to the measured points as shown on Figure 4. The width, depth and height are relative values, the point (0,0,0) is at the centre of the auditorium, and the limits (values +1 and -1) being at 2 m from the walls (horizontal coordinates) and at 50 cm from the desks or the ceiling.

The first measurement (A, in italics in the table), made with N_2O as tracer with the step down technique, had proven to begin with a bad tracer mixing, and therefore gives erroneous results. The next two measurements, B and C, made with SF6 successively with a step-up and a step-down technique provide results in close agreement, when account is taken of some uncertainty (± 2 to 3 minutes). The last two measurements, D and E, made simultaneously with the pulse technique, also show good agreement, the slight discrepancies with measurements B and C cannot be assumed to be significant.

The last two columns of this table provide the average and standard deviations of the results of measurements B to E. This shown mainly that the age of air is homogeneous. The only point which seems to differ significantly from the average is point 3,.close to the entrance door.

Table 1: Results of measurements of the age of air in the auditorium.

No	Width	Depth	Height	A N_2O *down*	B SF_6 step-up	C SF_6 down	D N_2O pulse	E SF_6 pulse	Av.	Std. dev.
1	0	0	-1	*19*	22	21	27	33	26	5
2	1	1	-1	*17*	26	21	24	25	24	2
3	-1	-1	-1	*30*	28	28	34	33	30	3
4	0	-1	0	*24*	23	25	29	27	26	2
5	1	0	0	*19*	21	23	19	21	21	1
6	0	1	0	*18*	26	23	21	24	23	2
7	-1	0	0	*19*	23	23	26	35	26	6
8	1	-1	1	*27*	26	25	30	25	27	3
9	0	0	1	*18*	24	25	21	25	23	2
10	-1	1	1	*23*	25	26	25	29	26	2
	Average			*21*	24	24	26	28	25	2
	Standard deviation			*4*	2	2	4	5	3	
11	Room mean age			*24*	28	27	26	23	26	2
11	Nominal time constant			*32*	30	29	29	27	29	2
	Efficiency			*65%*	55%	53%	56%	58%	55%	2%

The last lines of Table 1 show a good agreement between the average of the local mean ages and the room mean age measured at the exhaust grilles (point 11). Since this last measurement also provides the nominal time constant (about 30 minutes, that is 2 air changes per hour), the air change efficiency can be calculated and found to be 55%. Table 2 is another representation of the local mean ages (average of results B to E).

***Table 2:** Ages of air measured in the auditorium, in minutes, after the point number (No:age). The blackboard is at the bottom of the table. Locations at the desk level are written in italics, locations close to the ceiling are in bold.*

	Right	Centre	Left	Average
Back	**10: 26**	6: 23	*2: 24*	25
Middle	*7: 26*	**9: 23**	5: 21	24
		1: 26		
Front	*3: 30*	4: 26	**8: 27**	28
Average	28	25	24	

It is shown on Table 2 that, taking account of an uncertainty of ± 3 minutes on the measured ages, there are no significant differences between the locations. The averages of the ages measured at the desk level was 25 minutes, while the same calculation results in 27 minutes close to the ceiling and 24 minutes in between. Here again, no significant difference with the height.

In a second set of measurements, all the heights of the sampling points were changed to head height, that is 40 cm over the tables. The horizontal coordinates were kept the same, except for point 9, which was moved into the corridor. The results obtained are shown in Table 3.

Table 3: Results of measurements of the age of the air taken at head height.

No	Width	Depth	N2O pulse	SF6 step-up	Average	Standard deviation
1	0	0	27	24	26	2
2	1	1	24	23	24	1
3	-1	-1	26	28	27	1
4	0	-1	28	28	28	0
5	1	0	24	25	25	1
6	0	1	24	23	23	1
7	-1	0	28	22	25	4
8	1	-1	29	28	29	1
10	-1	1	28	23	25	4
	Average		27	25	26	1
	Standard deviation		2	3	2	1
9	Corridor		62	36	49	18
11	Room mean age		29	20	24	6
11	Nominal time constant		32	26	29	4
	Efficiency		55%	65%	60%	7%

The average values are shown on Figure 7. There, slight but significant differences can be observed: The oldest air is found in the corners at the left (close to the door) and right of the chair, while the youngest air is received at the two corners at the back of the room. Taking account of the uncertainties, the values measured at the exhaust are in agreement with the values measured before (Table 1). The ages measured in the corridor show that a fraction of the air provided by the ventilation is distributed into this corridor.

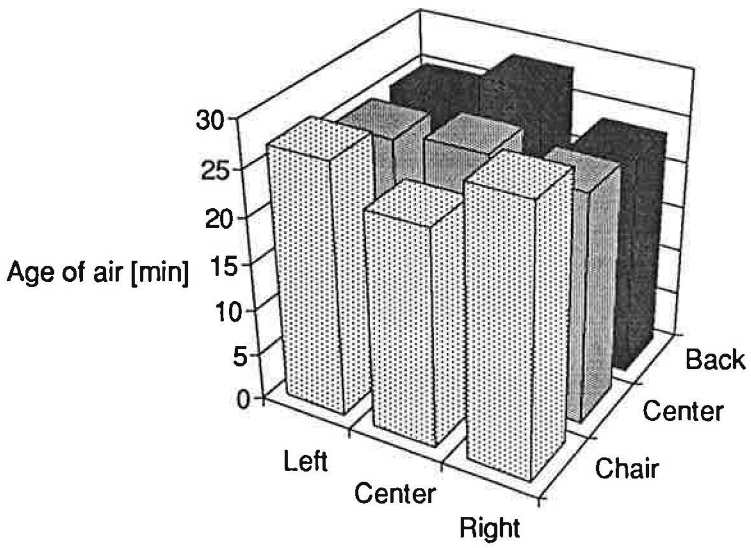

Figure 7: Representation of the age of the air at head height and at nine locations in the auditorium.

Conclusions

Detailed measurement have shown that the fresh air is evenly distributed in the auditorium. The position of the inlet and outlet grilles should however lead to a piston ventilation, at least partially. However, the shortcut in the ventilation system mixes nearly half of the exhaust air with fresh air, lowering the air change efficiency.

References

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[2] **Roulet, C.-A., Compagnon, R., and Jakob, M.:** A Simple Method Using Tracer Gas to Identify the Main Air and Contaminant Paths Within a Room. *11th AIVC Conference, Vol. 2, pp 265-278. Also in Indoor Air **3**, pp 311-322 (1991)*

[3] **Roulet, C.-A., Cretton, P.:** Field Comparison of Age of Air Measurement Techniques. *Roomvent 92, Aalborg, 1992.*

[4] **Sandberg, M. and Sjöberg, M.**: The Use of Moments for Assessing Air Quality in Ventilated Rooms. *Building and Environment **18**, pp 181-197, 1982. Airbase#1320*

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[6] **Sutcliffe, H. C.:** A Guide to Air Change Efficiency. *AIVC technical note 28, Bracknell, Berkshire RG124AH, GB, 1990. Airbase #4000*

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Communication

Sorry for not submitting an abstract for the next AIVC conference. We have nothing ready in the topics mentioned.

With kind regards, to everybody there.

Lausanne, 1992-03-26

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