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Ventilation Efficiency Measurements in a Test Chamber with Different Ventilation and Cooling Systems

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VENTILATION EFFICIENCY MEASUREMENTS IN A TEST CHAMBER WITH DIFFERENT VENTILATION AND COOLING SYSTEMS

Synopsis

Cooling ceilings are more and more proposed, in order to eliminate excess heat in office buildings without consuming much energy in air transport. On the other hand, piston ventilation is proposed to efficiently eliminate contaminants. These two systems may however interact and experiments were planned to look at these interactions.

Measurements of the age of air and air change efficiency were performed, together with more classical temperature and air velocity measurements, on various ventilation systems installed in the test chamber of Sulzer Infra, in Winterthur. The test chamber was arranged to simulate an office room, with heat generated from computers and occupants. Moreover, the contaminants from one occupant were simulated with a tracer gas and the contaminant removal effectiveness was measured at various locations in the room.

Six different series of measurements were performed with displacement ventilation, with two types of cooling ceilings. Two more tests were performed with mixing ventilation, using two different inlet grilles.

As expected, both mixing system, measured with the continuous cooling ceiling "on", reach nearly complete mixing, hence an air change efficiency close to 50 % and a uniform contaminant removal effectiveness close to 1.

Displacement ventilation systems showed a larger air change efficiency in most cases. However, the cooling ceiling counteracts the displacement and important mixing is observed when it is on, mainly if the air flow rate is lower than 5 volumes per hour. A test without cooling showed a strong displacement effect, the local mean age at every occupant location being lower than the room mean age. Except in this particular test, the contaminant removal effectiveness is generally about 1. It should be noted that, for these latter measurements, the contaminant source was not far from the inlet grilles, which represents the worst possible case.

It is also shown that systems with a high air change efficiency do not necessarily provide fresh air to the occupants.

1. Planning of the Experiment

1.1. Purpose of the experiment

The scope of the experiment is to evaluate various ventilation systems, that is to answer the following questions:
1. how does that ventilation system performs to bring fresh air to the occupants?
2. how does that ventilation system performs to evacuate contaminants from a room?

To answer question 1, the age of air was measured at various locations within the room. To evaluate question 2, a contaminant source is placed within the room, and the contaminant concentration is measured at various locations in the room.

However, within a limited budget, it was obviously not possible to perform extensive expensive experiments. The conditions in which the few possible experiments should be performed were hence carefully studied, using the theory of experimental planning , but also taking account of some comercial requirements.

1.2. Variables

Numerous parameters may have some influence on the internal air flow pattern, on the temperature distribution and on the indoor air quality. We can enumerate the following ones, without claiming to be exhaustive:

- parameters linked to the **room**: dimensions, furniture and occupancy, location and strength of the heat and contaminant sources, distribution and magnitude of infiltration paths, location of the occupants;
- parameters linked to the **ventilation system**: ventilation type, type and location of inlets and outlets, air flow rate, air temperature;

* parameters linked to the **heating and cooling systems**: type of these, installed power, temperatures.

A study involving variations of all of these parameters, even well planned, would be very large. To take account of the limited budget, the number of parameters allowed to vary in the present study were restricted. to a small number. In particular, the room was always the same: square floor 7,25 by 7.25 m, and 3 m height. Furniture, sources and simulated occupancy was installed as shown on figure 1.

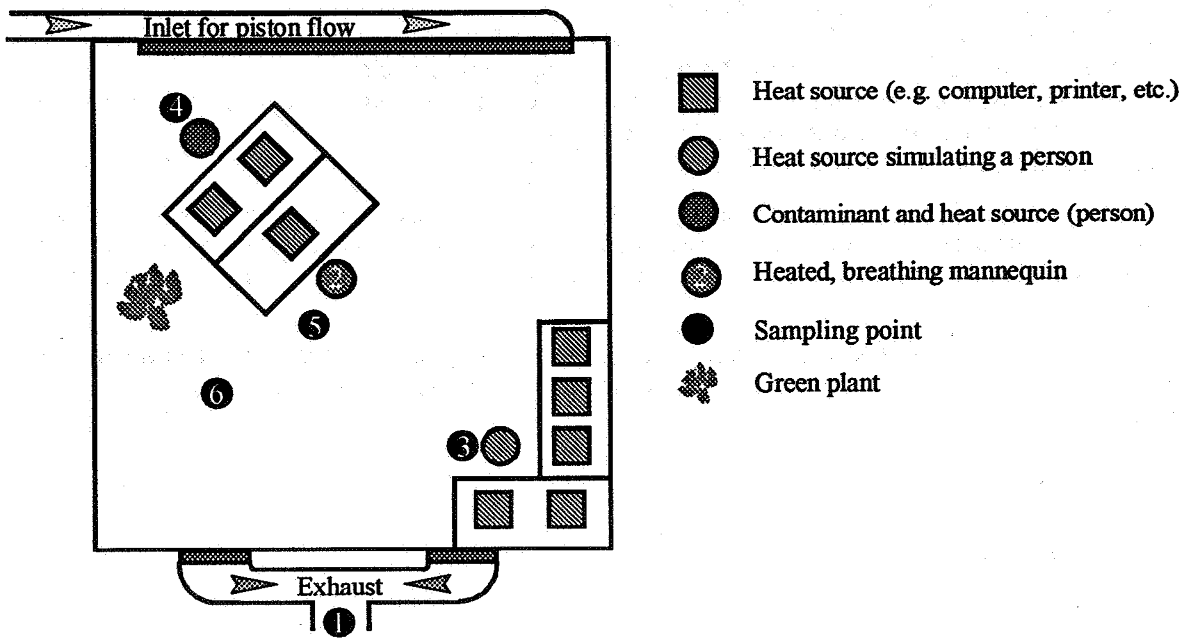


Figure 1: Plan of the test chamber with furniture, occupants and sampling points. Scale is 1:100. Sampling points are at 1.1 m, except at location 5 where air is sampled at 0.2, 0.7, 1.1, 1.3 and 1.8 m.

The parameters which were varied during this study are those shown on Table 1. Two ventilation systems (with variants) were tested, at various air flow rates. The internal heat load was evacuated partly by the ventilation, the other part being removed by a cooled ceiling, when on. Remaining planned parameters were:

* type of cooling ceiling, continuous or structured,
* internal load, related to floor area, in W/m²,
* air flow rate.

Table 1: Conditions in which the experiments were performed.

Experiment number	Ventilation system	Cooling ceiling		Air flow rate. m³/h	Internal load W/m²
I	Mixing (Vortex)	continuous	on	526	60
II	Mixing (Slots)	continuous	on	526	60
III	Piston	N/A	off	520	20
VI	Piston	continuous	on	268	60
VIII	Piston	continuous	on	788	60
IX	Piston	structured	on	268	60
X	Piston	structured	on	526	60
XI	Piston	structured	on	788	60

1.3. Location of the sampling points

An essential sampling point is the exhaust duct. The concentration of tracer gas at this location is required for the calculation of contaminant removal effectiveness, of specific air flow rate (air change rate) and of room mean age of air [1, 2, 3]. The location of the other points were chosen according to the following considerations:

* the total number of points should be limited to 6, which is the number of entries in the scanner;

- this number is not sufficient to perform a map of the concentration. Therefore, a mapping plan [4] is not appropriate in this case;
- the highest attention should be paid to the occupants.

As shown on figure 1, the sampling points are:

1 exhaust,
2 in the lungs of the breathing, heated mannequin;
3 close to the heated cylinder simulating an occupant at a working place in the corner, 1.1 m. high,
4 close to a similar cylinder at the desk, 1.1 m. high, facing the mannequin;
5 not far from the manikin, in order to see the difference between the environment of an occupant and the air it breathes, which could come from its plume,
6 at a location, 1.1 m. high, far from any occupant, heat source or wall.

For contaminant removal effectiveness measurements, N_2O was used as tracer, the source being the occupant 4. The tracer gas simulates any contaminant coming from that occupant, for example body odour or cigarette smoke. This occupant was chosen as a worst case, since he is away from the air exhaust grilles and close to the breathing mannequin.

Contaminant concentration was measured first at the 6 locations mentioned above, then at location 5 at 5 different heights, i.e. at 0.2, 0.7, 1.1, 1.3, and 1.8 m., to get an idea of the vertical distribution of the effectiveness.

2. Results

2.1. Age of air measurements

2.1.1. Experimental conditions

According to a recent sutdy [4], the step-up technique was used in all these experiments. The tracer gas (sulphur hexafluoride) was injected in the air inlet duct, at more than 5 m upwind the inlet grilles. In the first experiment, the injection location was a little closer, and imperfect mixing of the tracer gas was observed.

Samples of air were taken at fixed time intervals by the sampler and analysed with the Brüel and Kjaer 1302 photo acoustic analyser. The data were automatically recorded and interpreted to obtain the ages of air and their related confidence intervals at the various locations.

2.1.2. General results

The complete results, which can be found in [6], are summarised in Table 2. The average confidence interval at 95% probability for the age of air is about 1 minute.

Table 2: Summary of the results of age of air measurements.

Test No	Ventilation type	Cooling ceiling	Heat load W/m²	Flow rate m³/h	Local mean age of air [min] at location 1	2	3	4	5	6	Room mean age [min]
I	Vortex	Continuous	60	526	18	20	20	20	21	21	16
II	Slot	Continuous	60	526	22	21	22	24	24	26	20
III	Piston	Off	20	520	22	6	11	14	9	10	16
VI	Piston	Continuous	60	268	34	25	33	34	34	35	23
VIII	Piston	Continuous	60	788	17	6	16	16	18	19	12
IX	Piston	Structured	60	268	31	32	32	32	33	34	25
X	Piston	Structured	60	526	23	19	23	19	23	22	20
XI	Piston	Structured	60	788	18	8	15	15	15	14	14

2.1.3. Nominal time constant

The nominal time constant, t_n, can be estimated by two ways: from the ratio of the measured air flow rate in the ventilation duct and the room volume (157.7 m³ in the present case), or directly from the age of air in the exhaust duct. These two values does not fit in each case, as shown in Table 3.

The average relative difference is -12%, the time constant calculated from the tracer gas concentration at the exhaust being larger than this determined from the air flow rate. This systematic difference is larger than the confidence intervals (both being about 5 %) and should therefore be explained.

A possibility is a systematic error in the measurements, but it should be noted that the calibration of the analyser or the mixing of the tracer gas in the inlet air, which are the most probable errors, will have no influence on these results. Another explanation is that a part of the air does not leave the room through the exhaust duct, but through other leakage.

Table 3: Comparison of two estimates of the nominal time constant [minutes].

Test No	Nominal time constant $t_n(e)$ from exhaust	$t_n(a)$ from air flow	Dt/t
I	18	18	0%
II	22	18	-19%
III	22	18	-21%
VI	34	35	4%
VIII	17	12	-33%
IX	31	35	13%
X	23	18	-26%
XI	18	12	-38%

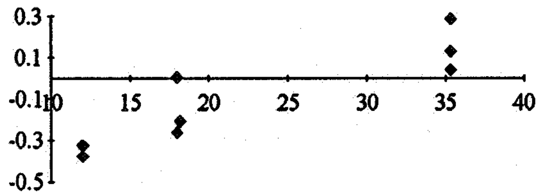


Figure 2: Relative difference between $t_n(a)$ and $t_n(e)$ versus $t_n(a)$

This second explanation is supported by the fact that there is an obvious correlation between the relative difference and the nominal time constant. As shown on figure 2, for small time constants (large air flow rates, thus high pressure differences) the difference is large and negative, meaning that the exhaust air flow rate is smaller than the inlet flow rate. For large time constants it is the contrary. Moreover, the room is at a higher pressure than the exterior.

2.1.4. Local mean age

Table 4 and Figures 3 and 4 show the ventilation efficiencies for each experiment and the relative local age, defined as the ratio of the local mean age and the room mean age at locations 1 (exhaust) to 6.

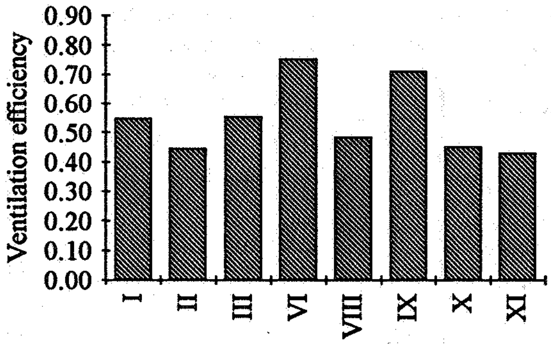
Table 4: Local mean ages related to room mean age at the measured locations for the various experiments.

Test No	Ventilation type	Cool	Local mean age / Room mean age at location 1	2	3	4	5	6	Room mean age [min]	Air change efficiency at exhaust	from flow
I	Vortex	on	1.09	1.19	1.20	1.21	1.26	1.29	16	0.55	0.55
II	Slot	on	1.08	1.06	1.08	1.20	1.21	1.27	20	0.54	0.45
III	Piston	off	1.37	0.39	0.67	0.84	0.57	0.61	16	0.68	0.55
VI	Piston	on	1.44	1.05	1.40	1.44	1.43	1.49	23	0.72	0.75
VIII	Piston	on	1.34	0.51	1.25	1.30	1.42	1.49	12	0.67	0.48
IX	Piston	on	1.25	1.27	1.29	1.30	1.35	1.36	25	0.63	0.71
X	Piston	on	1.18	0.98	1.17	0.94	1.15	1.09	20	0.59	0.45
XI	Piston	on	1.26	0.59	1.10	1.07	1.07	1.02	14	0.63	0.43

Only experiment III shows a mean age at every measured location in occupied zone smaller than the room mean age. In all the other cases, the average age of locations 2 to 6 is equal or higher than the room mean age. As far as the occupied zone is concerned, the piston ventilation is effective only in experiment III.

However, if one looks only at the manikin (location 2), it breathes an air fresher than the room average in experiments II, VIII and XI. These are the experiments with piston ventilation and high air flow rates.

Figure 3 right shows a predictable pattern: the ventilation efficiency for piston ventilation is higher than that of mixed ventilation. Figure 3 left does not seem to have any meaning. In particular, one case for mixed ventilation has a higher ventilation efficiency than several piston systems. On the right figure, measurement techniques used for both times involved in the calculation of ventilation efficiency (i.e. nominal time constant and room mean age of air) are the same, thus explaining the coherence. These figures seem to show that the air flow rate measured in the ducts was not equal to the air flow rate at the exhaust. Therefore, the reference nominal time constant taken in the present paper will be the one measured with tracer technique at the exhaust grilles



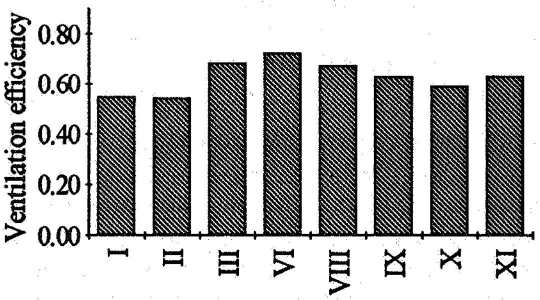
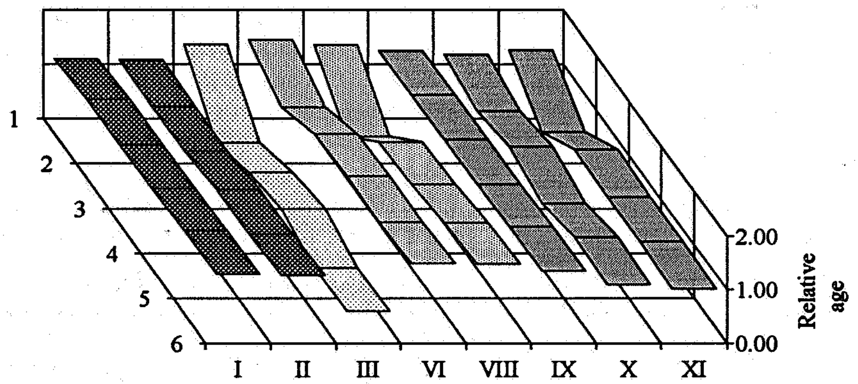


Figure 3: Ventilation efficiencies for the various experiments. At the left, the nominal time constant is calculated from the air flow rate. At the right, the nominal time constant is taken as the age of air at the exhaust.

Figure 4 shows clear differences between the various systems. It should be noted, that the measurement accuracy shall be taken into account when comparing the various figures. To be significant, any difference should be larger than the confidence interval. The error in the age of air is about 1 minute, that is 3 to 5 %. The error in the room mean age is similar. Therefore, errors in relative age or in ventilation efficiency is 5 to 10%.

Figure 4: Local relative ages (compared to the room mean age) at the measured locations for the various experiments.



When compared to all the other measured systems, system III gives the youngest air to the occupants. This is a piston ventilation system, and the only one without cooling ceiling. Nevertheless, its global efficiency is not better than systems VI and VIII, which are similar but with cooling ceiling on. A global, room averaged parameter provides an average information, but does not show local differences, which could be dramatic, as, for example, those observed on figure 4 between case III and cases VI and VIII. See also the system IX, with an air change efficiency of 0.63 and a relative age of air higher than the room average for every occupant. This shows that, as far as the occupants are concerned, global parameters, like the ventilation efficiency, should be used with care.

The exhaust presents in all cases, as it should be, a relative age equal or higher than the other places. The youngest air reaches first the mannequin (location 2), then the cylinder 4. That is a surprise, since cylinder 4 is closer to the inlet grilles. Maybe the air takes some time to climb at 1.1 m, where the sampling tubes are. In general, relative differences in the relative age of air in all systems with cooling ceiling are larger when the air flow rate is high (systems VII, and XI)

As it could be expected, the mixed ventilation systems (experiments I and II) present a ventilation efficiency close to 0.5 and an homogeneous age of air. However, some piston systems (e.g. IX or X) do not perform much better. In the systems studied, the cooling ceiling seems to maintain the air at a low level or to mix the air within the room.

2.2. Contaminant removal effectiveness

This effectiveness was measured at the same locations as the age of air, the contaminant source being cylinder 4. This location for a contaminanting person (e.g. a smoker) is the worst one. The complete results from these measurements are given in reference [6], and summarised on Table 5 and Figures 5 and 6.

Basically these measurements were planned to be taken at steady state, after constant injection of tracer gas around cylinder 4. Assuming zero background concentration, the contaminant removal effectiveness is obtained by dividing the tracer gas concentration measured at the exhaust by the concentration at the places of interest.

Table 5: Contaminant removal effectiveness at various locations, when contaminant is coming from cylinder 4, at 1.1 m high. Results in italics are dubious.

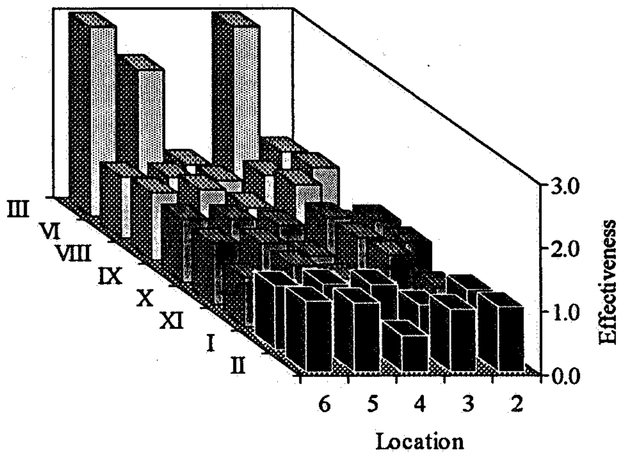
Test	Contaminant removal effectiveness at									
	Manikin	Cylinder	Cylinder	Zone	Zone	Height at location 5 [m]				
No	2	3	4	5	6	0.2	0.7	1.1	1.3	1.8
I	0.9	0.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
II	1.0	1.0	0.6	1.1	1.1	1.1	1.1	1.0	1.1	1.1
III	1.0	13.6	0.8	2.3	5.1	1.0	1.1	2.2	*14.8*	1.4
VI	1.1	1.0	0.9	0.9	1.0	2.4	1.2	1.0	0.9	1.0
VIII	*0.6*	*1.2*	*0.8*	*1.1*	*1.1*	1.9	2.2	1.4	1.3	1.3
IX	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
X	1.0	1.1	0.8	1.0	1.0	0.4	0.7	0.9	1.0	1.0
XI	0.6	1.1	0.8	1.0	0.8	0.4	0.4	0.9	0.9	0.9

The contaminant removal effectiveness equals 1 for complete mixing, can be lower if the concentration at location is higher than at the exhaust (bad removal), and higher if the concentration is small.

Here again, system III, without cooling, presents the largest differences. With a few exceptions, all the other systems have a contaminant removal effectiveness close to 1. The exceptions are as well for piston ventilation (in the mannequin, for experiments VIII and XI and for mixed ventilation (system II at location 4).

As it should be, location 4, which is at the contaminant source, presents generally the worse effectiveness. The mannequin, located downwind and not far from cylinder 4, also presents in some case a poor effectiveness. The best place, with regard to that source of contaminant, is at location 3, in the opposite corner of the room.

Figure 5: Contaminant removal effectiveness at various locations, when contaminant is coming from cylinder 4, at 1.1 m high. Value at locations 6 and 3 for experiment III are out of scale (effective values: 5 and 14)



The differences between piston ventilation systems and mixed systems are more obvious on Figure 6, which shows the vertical distribution of the contaminant removal effectiveness at location 5, that is in the vicinity of the mannequin. All the mixed systems have an effectiveness close to one, from floor to ceiling, while most piston ventilation systems show differences. The exception is system IX, with structured cooling ceiling and low air flow rate, which is homogeneous.

The best figures are obtained in system III, at 1.3 m, and for systems VI and VIII, close to the floor. The worst case, at location 5, is for systems X and XI, close to the floor. However, this level does not need to be well ventilated, since only small pets may breath at that height.

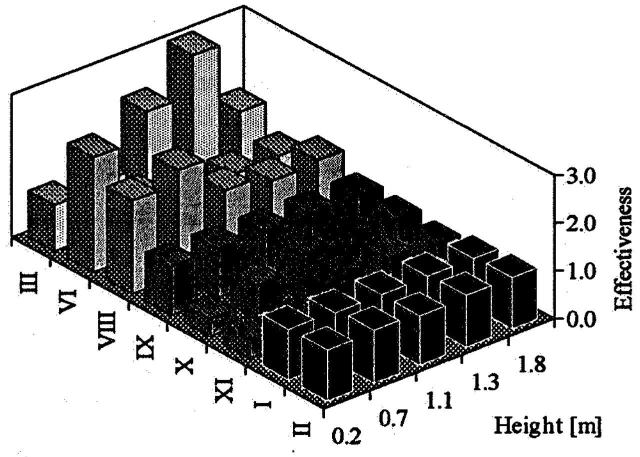


Figure 6: Contaminant removal effectiveness at various heights, at location 5, when contaminant is coming from cylinder 4, at 1.1 m high. Value at 1.3 m for experiment III is out of scale (15).

3. Conclusions

Ages of the air and contaminant removal effectiveness were measured at several locations in a test chamber, for three different ventilation systems (piston type, and two different mixing systems), with and without cooling ceiling (also two different types). The ventilation efficiency is also obtained for each of these cases.

Mixing systems show a very homogeneous pattern, as it was expected. The homogeneity is the highest for large air flow rates. At the same air flow rates, the system with slot inlets does not show significant differences when compared to the vortex inlets.

Piston ventilation system works well when the cooling ceiling is off, or when on, if the specific air flow rate is high (in this case, higher than 3.3/h). The effect of the cooling ceiling is to counteract the upward piston ventilation and to induce a partial mixing. This effect seems stronger when the cooling ceiling is not continuous.

Among the values tested, the largest air flow rates showed the greatest piston effects, as far as the ages of air or contaminant removal at occupied locations are concerned. The conclusion is changed if the global ventilation efficiency is taken as reference. This shows that this latter parameter should be used with care.

4. Acknowledgements

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