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CONTAMINANT REMOVAL PERFORMANCE IN TERMS OF VENTILATION EFFECTIVENESS

Eimund Skåret
Norwegian Institute of Technology,University of Trondheim, Norway

Abstract

The paper shows that age analysing technics are an excellent tool to assess ventilation effectiveness. It is important to differ between air exchange effectiveness and contaminant removal effectiveness, having continuous generation of contaminants. Only when asource is homogenious and passive, the age of the air and the contaminants in the room are equal. However, the air exchange effectiveness accounts for the removal effectiveness of the contaminants left in the room when the generation stops. Tests reported show how different air and contaminants can behave in a ventilated room and are concequently an excellent demonstration of the statements.

Introduction

The ventilation process

The main objectives of ventilation are to renew the room air and to remove contaminants generated within the actual space. In the past the air exchange frequency, i.e. the ventilation air flow rate divided by the room volume, $1/\tau_n$, has been widely used to quantify this process. This quantity, which in principle is nothing more than the specific nominal air flow rate, was by no means satisfactory to express neither air renewal nor air quality. A more varied and comprehensive description of the ventilation process was needed, and there has actually been carried out substantial research work within this area during the last five years. Two approaches has been used:

1. Multicell air diffusion theory (1, 2, 4, 5).
2. Age distribution theory (2, 3).

Important conclusions so far are that:

The ventilation air.

1. Air and contaminants distributes differently in a ventilated space.

2. The turnover time for the ventilation air flow through the room (average age of the air in the exhaust, taken as the time elapsed from the moment the air enters the room) is always equal to, τ_n,(the room volume divided by the ventilation air flow rate). The flow patterns does not mean anything in this connection.

3. The turnover time (average air exchange time) for the total volume of air in the room is twice the average age for the air in the

room, taken as the time elapsed after the air entered the room. (The time for filling the whole room with new air is equal to the time necessary for the air to leave the room). Now the air flow patterns become important and concequently one finds that this time quantity differs significantly between different ventilation systems. Simply spoken, during the process of filling the room, more or less air is lost through the exhaust before all the room is filled up with new air. One can imagine this process as follows: Taking any arbitrary zero time, the turnover time for the air in the room is now the average time it takes for every molecule of the air, that were in the room at time zero, to be replaced by a new molecule.

In fact, only when the air flows as a piston through the room (plug flow), the turnover time for the air in the room is equal to the turnover time for the air flowing through the room. Else, the average exchange time is greater, increasing to the double at complete mixing between room air and ventilation air.

Usually, we are used to characterize the flow as shortcircuiting when the average age of the air in the room is greater than the average age of the air in the exhaust (having complete mixing these ages are equal). In reality, shortcircuiting takes place at once the flow patterns deviate from plug flow.

4.The air is on the average fresher the shorter its age is. There are generally two distinct flow regions in a ventilated room, the supply region (where the air enters the room), and the rest of the room. The average age of the air in the supply region is shorter than in the other region. The average age of the air in the other region becomes shorter if the exhaust air in addition is taken from that region. At the same time this also makes the average age of the air in the supply region shorter (displacement or plug flow effect). The concequence of this should be obvious.

The contaminants.

1. Air quality, which can be expressed as the concentrations of contaminants, are not directly related to the air renewal process described. In studying the age of the contaminants one finds that it is lowest in the "supply" regions of the contaminants, and concequently their concentration are at the highest there. Analysing air quality in terms of "age" is therefore in a way "inverted" compared to the air renewal analysis.

2. The turnover time for the contaminants are, contrary to the situation for the ventilation air, dependent on the flow patterns for the total system. It can be shown (3) that the room average concentration of a contaminant in the room is proportional to its turnover time, obeying the following rule at steady state conditions:

$$\frac{\langle C_i \rangle}{C_e(\infty)} = \frac{\tau_t}{\tau_n} \qquad (1)$$

$C_e(\infty)$ = $\dot{m}/\dot{V}$

$\dot{m}$ = production rate of contaminants

$\dot{V}$ = ventilation air flow rate

τ_n = $V/\dot{V}$= Turnover time for the ventilation air flow

V = room volume

$(C_e(\infty)$ = steady state concentration in the exhaust air
$\langle C_i \rangle$ = average concentration in the room
τ_t^c = turnover time for the contaminant flow

The more the contaminant flow are shortcircuited to the exhaust, the lower the turnover time.

Displacement flow of ventilation air promotes shortcircuiting of contaminants. However, the contaminant source may be of the active type (has its own momentum flux or has a buoyancy) creating its own flow pattern. This makes it difficult to predict turnover times for the contaminant flow based on age determination for the air in the room.

Local concentrations may vary considerably, leading to that air quality can finally be determinated only from measurements of the concentrations of all the actual contaminants in the room. However, the more distributed, homogenious and passive the sources are, the better the correlation is between air quality and average age of the air in the room.

Contaminant removal and air exchange performance. To sum up, the average performance or effectiveness of a ventilation system at steady state can be expressed as the ratio between the turnover time for the ventilation air flow and the turnover time for the contaminant flow.

$$\bar{\varepsilon}^c = \frac{\tau_n}{\tau_t^c} = \frac{C_e(\infty)}{\langle C_i(\infty) \rangle} \qquad (2)$$

The local air quality index can be expressed as:

$$AQI = \frac{C_e(\infty)}{C_i(\infty)} \qquad (3)$$

$C_i(\infty)$ = local steady state concentration.

The air exchange effectiveness can be expressed as the ratio between the turnover time for the ventilation air and the turnover time for the air in the room:

$$\bar{\varepsilon}_e = \frac{\tau_n}{2 \langle \bar{\tau}_i \rangle} \qquad (4)$$

The inverted slope of the last part of the decay curve, λ_e, after a complete stop in contamination generation, is an indicator of the numerical value of the quantity $\langle \bar{\tau}_i \rangle$ (3, 5). $\bar{\varepsilon}_e$ may therefore be roughly expressed as:

$$\bar{\varepsilon}_e = \frac{1}{2} \tau_n \lambda_e \qquad (5)$$

In the following the importance of the introductory statements are exemplified through results from some tests in a 27 m^3 test chamber.

LABORATORY TESTS

Experimental setup.

Tests were carried out in a 27 m^3 test chamber: 3,45 x 3,45 x 2,3 m^3. There were alltogether 33 sampling points for tracer gas concentrations in the room, plus 1 point in each of the supply and exhaust ducts, after the fan. Point 1-9 was located 16 cm above floor level, point 10-18: 116 cm above floor level and point 19-27: 216 cm above floor level. Point 28-33 was located 50 cm from the source, N-S, E-W, U-D. N_2O was used as tracer gas for simulation of the contaminant sources. N_2O, N_2 and O_2 was premixed on bottles to specified source densities and N_2O concentrations. Certified calibration gases were used for continuous calibration of the gas analyser. The gas analyser used was of the IR type with an output voltage linearized to gas concentration. The time constant for the analyser was only 2 sec., allowing for taking samples each 8 sec.. Further discription of the sampling system is omitted here.

The objectives of the tests made were partly to demonstrate the usefulness of age analyses to assess air quality and describe the flow patterns in a ventilated space, and partly to examine how details like ventilation schemes, heat sources and types of contaminant sources are likely to influence on the contaminant removal effectiveness. Three different ventilation schemes were used:

1. Exhaust only (air supply through leakages). Exhaust was located in a corner just below the ceiling.
2. High wall slot (plane jet) supply. Exhaust as 1.
3. Low velocity floor supply. Exhaust as 1.

Two types of contaminant sources were simulated:

1. Line source with higher density than the room air.
2. Passive point source with neutral density.

Only tests with point source are reported in this paper. The mechanical exhaust air flow was always greater than the mechanical supply air flow, in order to make sure that all ventilation air was passing the exhaust duct.

For the tests reported in this paper, the supply air temperature was below the room air temperature. Also, the room was kept at a temperature slightly higher than the temperature of the surroundings, creating weak downward convective currents along the walls, except for one wall that was slightly heated, creating an upward convective current along that wall.

Results

Test no. 5, fig.1. This is a test with exhaust only, .55 ach., and a neutral point source, as indicated. The mean concentration of the tracer gas in the room is lower than in the exhaust $\tau_t < \tau_n$. On the other hand, the air exchange indicator, $1/\lambda_e$, indicates shortcircuiting: $\langle\bar{\tau}_i\rangle > \tau_n$ (air exchange efficiency lower than 40%). The reason for this is that the warm wall transports air to the exhaust. Low concentrations at the floor indicates much infiltration at low levels. This air is caught in the convective currents, also carrying relatively large amounts of the contaminant. In the breathing zone, point 10-18, the air quality index shows the same air quality as for complete mixing, i.e. the breathing zone does not benefit from a low mean concentration. On the other hand, the breathing zone is not suffering from the shortcircuititing of ventilation air compared to complete mixing. In this case the shortcircuiting of ventilation air is compensated for by shortcircuiting of contaminants. The gross flow patterns, based on the measurements, are indicated in the figure.

<u>Test no. 15, fig.2.</u> Low velocity air supply at floor level, exhaust under the ceiling as indicated, 2 ach and a neutral point source. Supply air tempetarure was kept lower than room air temperature. $\langle\bar{\tau}_i\rangle \approx 1/\lambda_e > \tau_n$. ($\varepsilon_e < 40\%$ for the same reason as for test 5. However, the air quality indicator is higher, i.e. the air quality in the zone of occupation is better, in spite of a higher average concentration in the room). $\tau_t < \tau_n$, which means that contaminants are shortcircuiting here too. The shortcircuiting of contaminants is not that as much pronounced as for test no. 5. The shortcircuiting of ventilation air is more than compensated for by the shortcircuiting of contaminants. The flow patterns are indicated in the figure. Usually this type of ventilation scheme exhibits displacement qualities for the ventilation air flow. This flow pattern is here destroyed by the convective currents along the heated wall.

<u>Test no. 21, fig 3.</u> High wall slot, high velocity air supply, exhaust as for the other tests , neutral point source. Supply air temperature lower than room air temperature, 2 ach.. This scheme has the highest turbulence intensity. The concentrations are nevertheless rather uneven, and rather high at floor level, point 1-9. There is no shortcircuiting of contaminants. $\tau_t \approx \tau_n$. On the other hand, the ventilation air exhibits shortcircuiting $\langle\bar{\tau}_i\rangle \approx 1/\lambda_e > \tau_n$ ($\bar{\varepsilon}_e < 40\%$). This is due to the fact that the exhaust air is partly taken from the supply region. The convective currents up along the warm wall create a secondary zone not communicating with the exhaust. The figure shows the flow patterns, based on the tracer gas analyses.

<u>Conclusions</u>.

The average air exchange effectiveness alone does not account for the air quality in the zone of occupation. The measurements of the turnover time for the contaminants improves the information and gives qualitatively the right information. Measurements of the actual concentrations of contaminants give the most accurate information. Air exchange effectiveness measurements would have ranged test no. 21 as best, turnover time measurements for the contaminant would have ranged no. 5 as best, while concentration measurements range no.15 actually as no. 1, followed by no. 5, leaving no. 21 to be poorest, quite contrary to what the air exchange effectiveness would have predicted.

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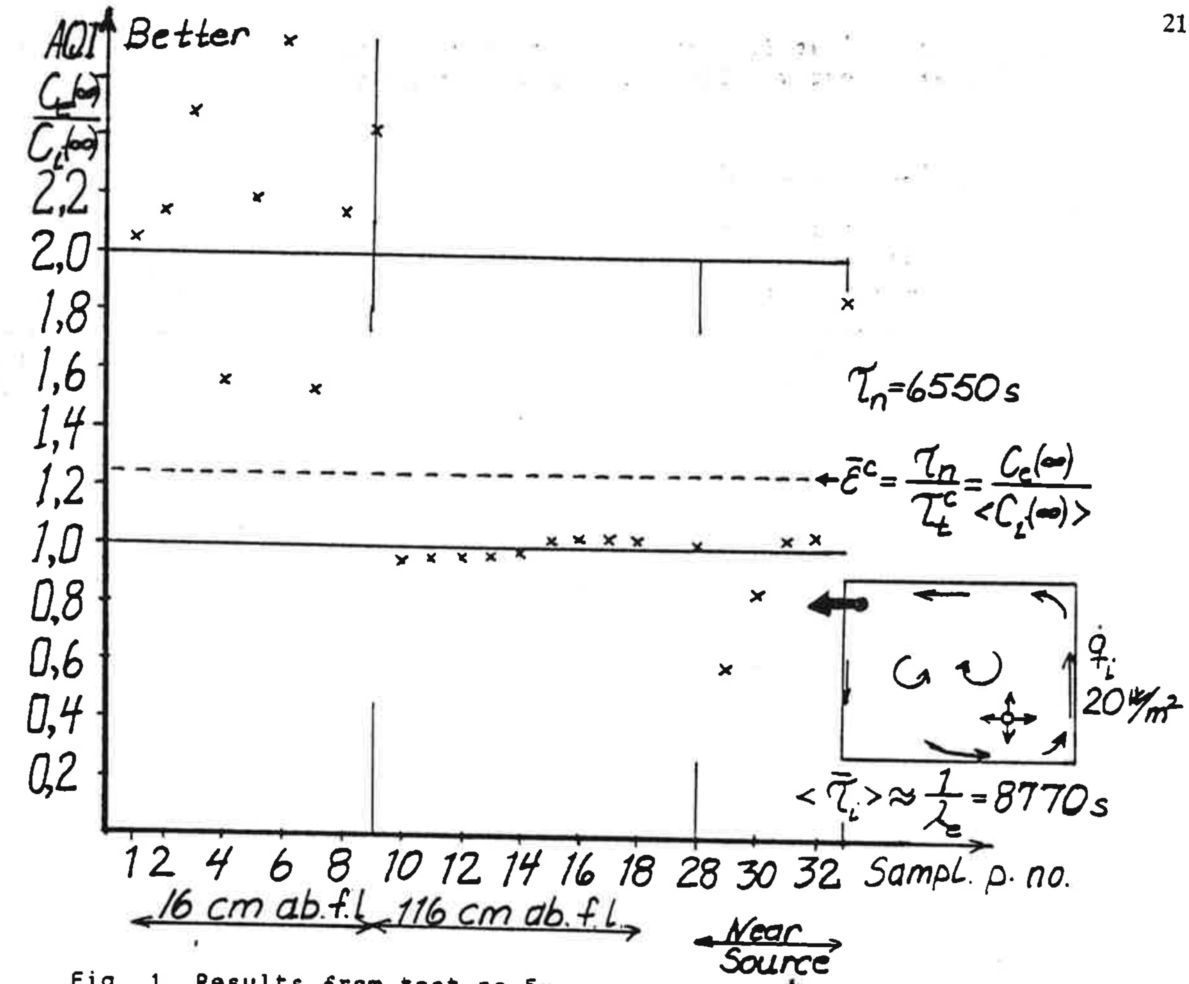

Fig. 1. Results from test no.5.
Exhaust only, neutral point source,
x = AQI

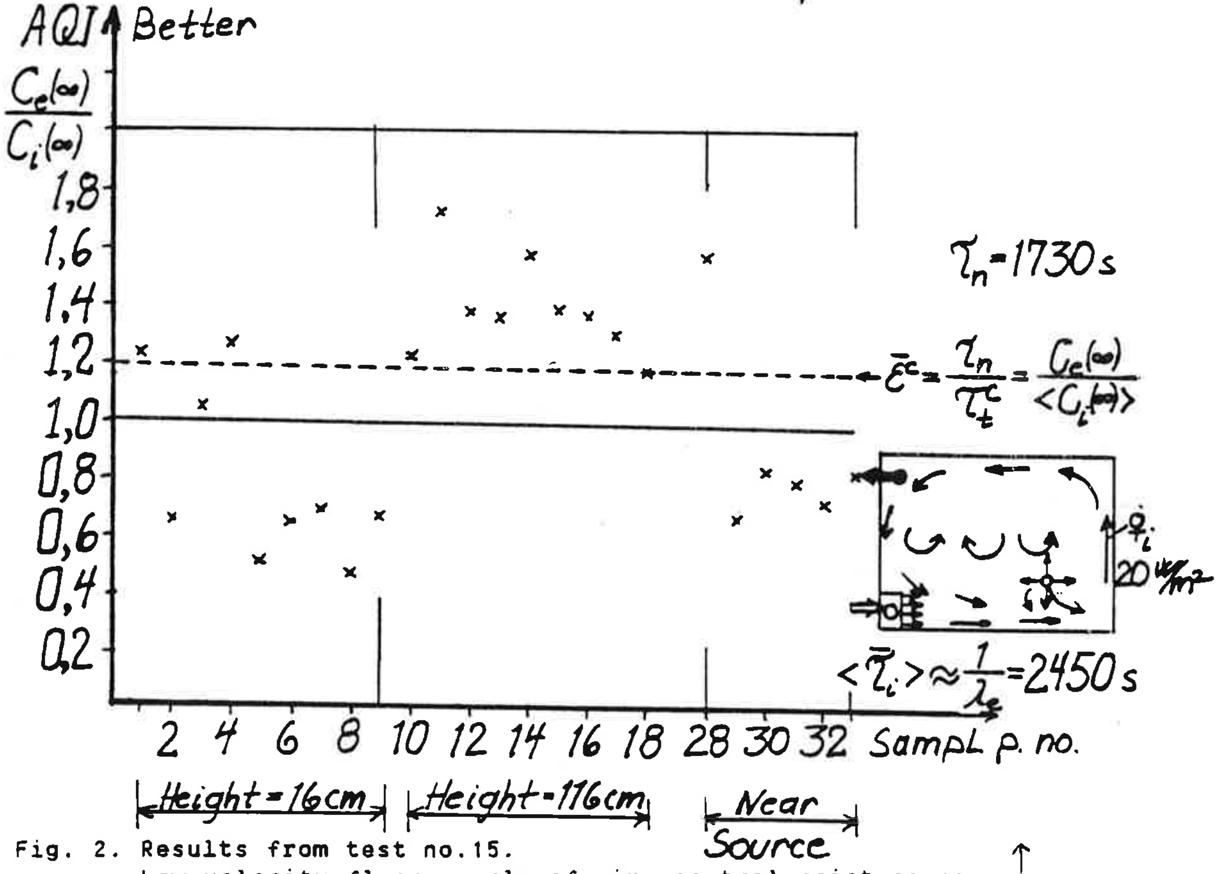

Fig. 2. Results from test no.15.
Low velocity floor supply of air, neutral point source,
x = AQI

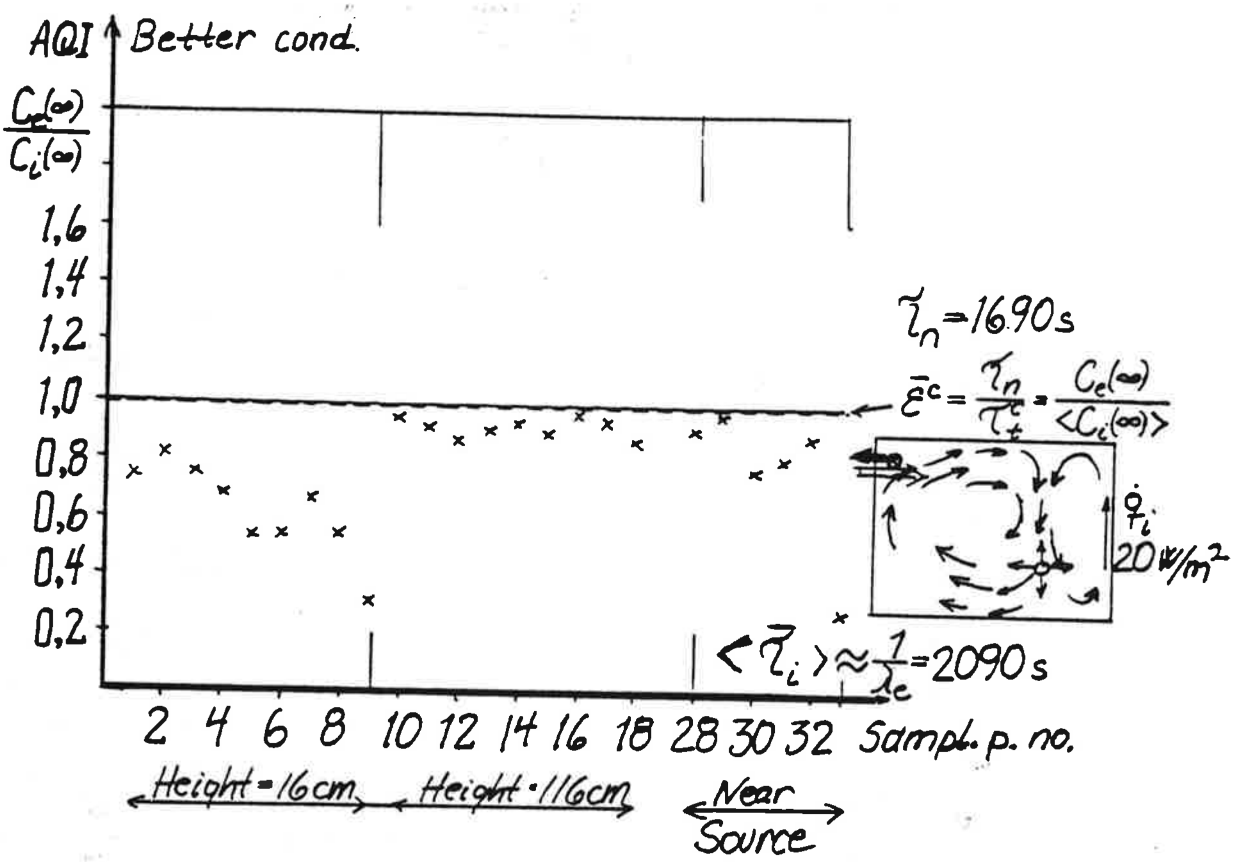

Fig. 3. Results from test no.21.
High wall plane jet(slot) supply of air, neutral point source
x = AQI