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Ventilation Measurements in a Cinema

Y Jin, B R Sørensen, S E Sveen

Narvik Institute of Technology, N-8501 Narvik, Norway

VENTILATION MEASUREMENTS IN A CINEMA

Y. Jin, B.R. Sørensen and S.E. Sveen
Building Science
Narvik Institute of Technology
N-8501 Narvik, Norway

SYNOPSIS

This paper reports on the ventilation measurements in a cinema using the tracer-gas technique. Both the local and room air exchange efficiencies were measured. The two tracer-gas methods, "step-up" and "step-down (decay)", were used alternately when the cinema was in use to enable a continuous measurement of air-exchange efficiencies under various occupancies. The air exchange efficiencies were found to be very close to that for a perfect mixing, with little influence from the occupants. This might be due to that the cinema had a downward mixing ventilation with a large air change rate. The air exchange efficiencies were found to be lower with the decay method than with the step-up method. The results also show that the decay method was more stable than the step-up method for evaluating the local air exchange efficiencies. However, both are stable for evaluating room air exchange efficiencies.

Other parameters such as the CO_2 concentrations and temperatures were also measured. Due to good mixing in the cinema, the thermal stratification was found to be small. However, the difference between the CO_2 concentrations in the occupied zone was found larger with higher occupancy. The CO_2 concentrations were found to be higher in the occupied zone than the room-average ones.

1. INTRODUCTION

The main objective of ventilation is to achieve good air quality for the occupants. How the fresh air is distributed to the occupied zone and the pollutants are removed from the space are of particular interest for HVAC engineers. The introduction of the "age of air" and the development in experimental methods with tracer-gas technique facilitate the study of the air distribution and flow pattern in a ventilated space.

The mean-age of air in a room is the time it takes, on an average, to replace (exchange) the air present in the room. Its value can be used to determine whether the space is well ventilated or whether there are stagnant zones present. However, to determine whether the stagnant zone is located in the occupied zone requires the measurement of the local mean age of air. With a multi-channel tracer-gas equipment, the flow situation in a room can be examined.

In this study, a small cinema was chosen for the measurement of the air exchange efficiencies. In addition, the temperatures and CO_2 concentrations were also measured.

2. EXPERIMENTAL SET-UP

The cinema being investigated was located in the centre of a town in northern Norway. It had a floor area of about 120 m^2 and a seating capacity of 60 persons. The effective volume was about 340 m^3. Figures 1 and 2 show schematically the cinema.

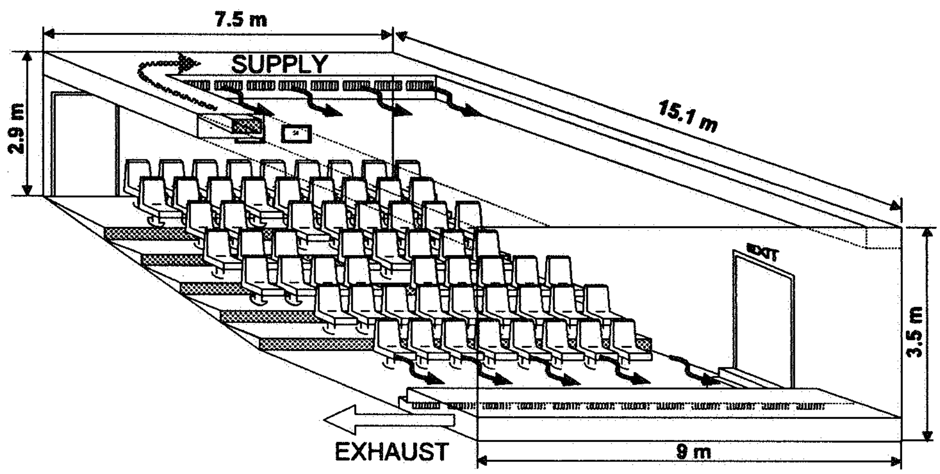


Figure 1. Illustration of the cinema.

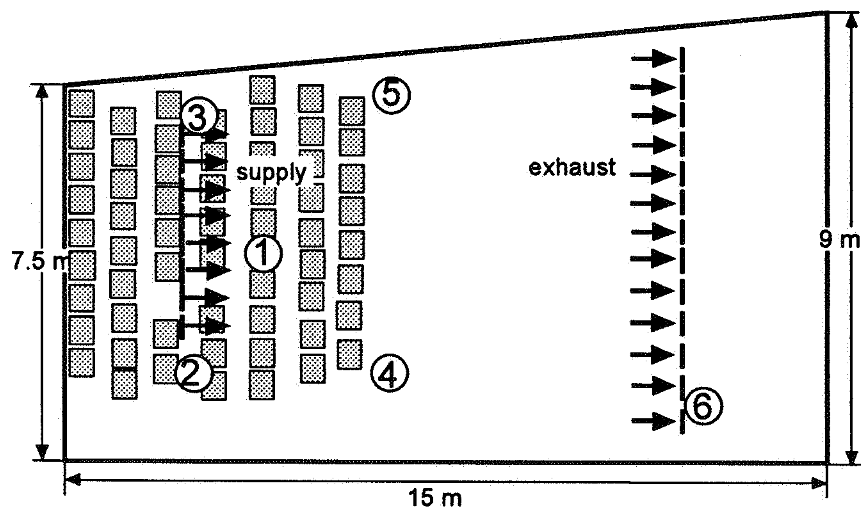


Figure 2. Plan of the cinema and sampling locations.

The cinema was situated underground, so the outdoor climate had little influence on the indoor climate. It had a downward mixing ventilation system, and no heating or cooling devices were used within the cinema. There were eight rectangular air terminal devices used at the supply and 13 at the exhaust, measuring 0.1×0.5 m (height × width) each. Figure 3 shows schematically the ventilation system for the cinema.

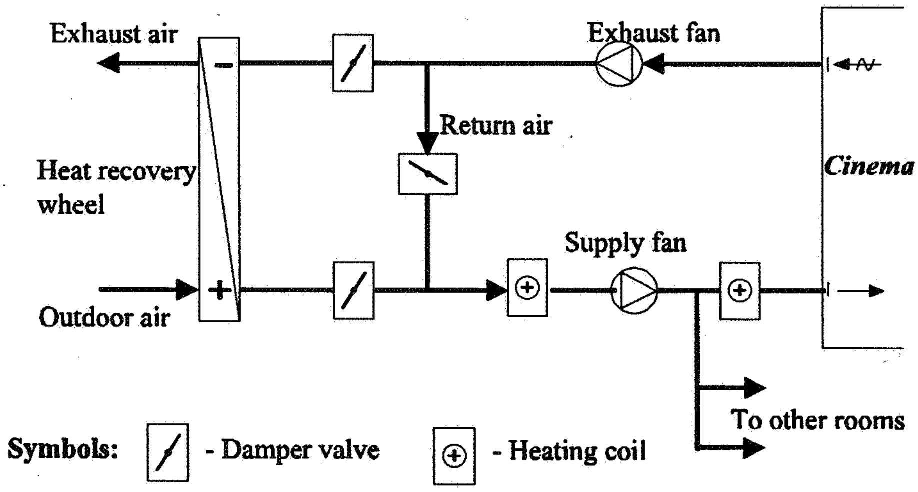


Figure. 3. Schematic diagram of the ventilation system for the cinema. The return-air damper was closed during the measurement.

The measurements were carried out at six sampling points. The locations of the sampling points and the parameters measured can be found in figure 2 and table 1. The tracer-gas used was SF_6 (sulphur hexafluoride).

Table 1. Parameters measured at various sampling points

Sampling points	Height over the floor (m)	Measured parameters		
		Temperature	CO_2 conc.	SF_6 conc.
1	0.8	yes	yes	no
2	1.6	yes	yes	yes
3	1.6	yes	yes	yes
4	1.6	yes	yes	yes
5	1.6	yes	yes	yes
6 (exhaust)	0.2	yes	yes	yes

The temperatures were measured continuously at all six sampling points with thermal couples. Additional five thermal couples were placed vertically near sampling point 4, spaced evenly between the heights 0.5 m and 2.5 m for determining the vertical temperature gradient. These thermal couples were all calibrated with a precision thermometer.

CO_2 concentrations were measured at all the six sampling points. At sampling point 1, a portable CO_2 monitor manufactured by Fläkt, Sweden was used. At sampling points 2 to 6, both CO_2 and SF_6 concentrations were measured using a multi-gas monitor together with a multipoint sampler and doser (Brüel and Kjær model 1302 and 1203). They can provide a maximum of six channels for sampling and analysis of six different gases at the same time, of which five were used during the measurement. Descriptions of these instruments and the application software for data acquisition are given in (1,2).

The measurements were carried out during two consecutive evenings. Two films with a length of 1.5 to 2 hours were shown during each evening. There was a 20 to 30 minutes pause between the two films. Measurements started a couple of hours prior to the first film. The occupants were 2 respectively 9 the first evening, and 22 respectively 16 the second evening.

3. TRACER STEP-UP AND STEP-DOWN (DECAY) METHODS

The theory on the age of air and air exchange efficiency has been well established, and they can be determined by the two commonly used methods: the tracer step-up and tracer step-down (decay) methods (3,5,6). The local mean age of air at a particular point p, $\bar{\tau}_p$, can be determined using these two methods (see figure 4):

$$\bar{\tau}_p = \frac{\int_0^\infty [C(\infty) - C(t)]\mathrm{d}t}{C(\infty)} = \frac{\text{Area above the step-up curve}}{C(\infty)} \text{ (for step-up method)} \quad (1)$$

and

$$\bar{\tau}_p = \frac{\int_0^\infty C(t)\mathrm{d}t}{C(0)} = \frac{\text{Area under the decay curve}}{C(0)} \text{ (for decay method)} \quad (2)$$

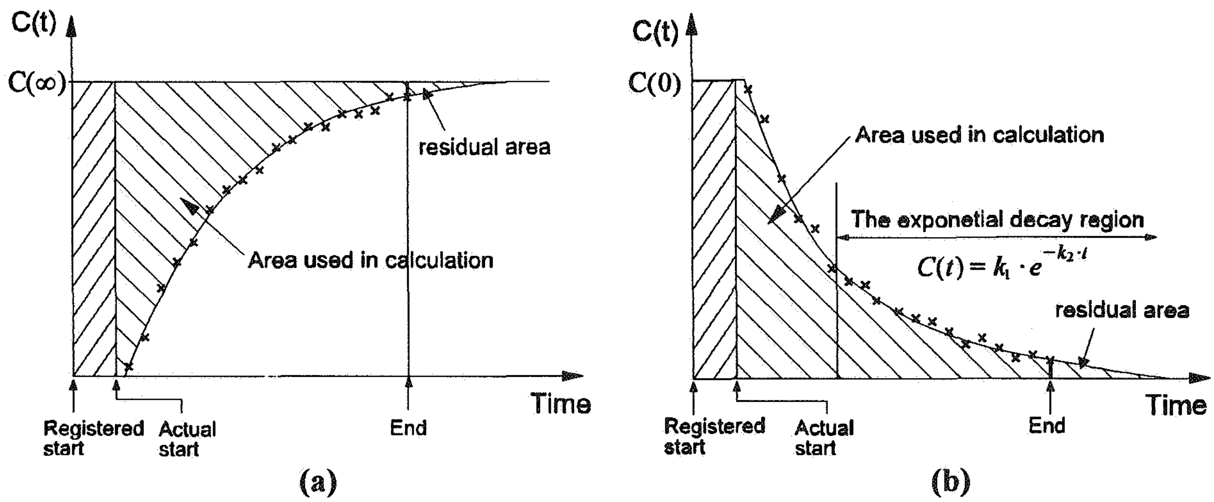


Figure 4. (a) Step-up method, and (b) Step-down (decay) method.

The areas used both in equations 1 and 2 consist of two parts: the first part is obtained using the measured data sets; the second part is the residual part, which can be obtained using the extrapolation method with the exponential functions (2,4).

Notice that the length of the dosing and sampling tubes will cause a time delay during the measurements. This time delay is the one for tracer to be transported in the tubes. The areas used for calculation should be the ones from the actual start time.

The local air exchange efficiency at point p, ε_p, is

$$\varepsilon_p = \frac{\tau_n}{\tau_p} \times 100\% \tag{3}$$

where τ_n is the nominal time constant, $\tau_n = V/q_v$, V is the room volume and q_v is the ventilation flow rate.

The air exchange efficiency for the room, ε_a, is defined as (3)

$$\varepsilon_a = \frac{\tau_n}{2 < \bar{\tau} >} \times 100\% \tag{4}$$

where $< \bar{\tau} >$ is the room mean age, which can be calculated from

$$< \bar{\tau} > = \frac{1}{\tau_n} \int_0^\infty t \cdot \left(1 - \frac{C_e(t)}{C_e(\infty)}\right) \mathrm{d}t \qquad \text{(for step-up)} \tag{5}$$

and

$$< \bar{\tau} > = \frac{\int_0^\infty t \cdot C_e(t) \mathrm{d}t}{\int_0^\infty C_e(t) \mathrm{d}t} \qquad \text{(for decay)} \tag{6}$$

where C_e is the tracer concentration at the exhaust.

4. RESULTS AND DISCUSSION

4.1. Air exchange efficiency

The measured tracer concentrations at five sampling points 2-6 are shown in figure 5.

The ventilation flow rate can be measured accurately using the tracer-gas technique (7). With a constant dosing method and the measured downstream concentration, the ventilation flow rate, q_v, is

$$q_v = \frac{\text{dosing rate}}{\text{downstream tracer concentration}} \tag{7}$$

The measured downstream tracer-gas concentrations in the supply duct to the cinema are shown in figure 6. The supply air flow rate was found to be 2150 m^3/h with very small variations with time. This gives an air change rate of 6.3 h^{-1}. By measuring the upstream concentration, the amount of return air or short-circuiting air through the heat recovery wheel can be also be determined. The short-circuiting air was found to be less than 3% the fresh air, thus no considerations were taken on the background tracer concentration in the supply air.

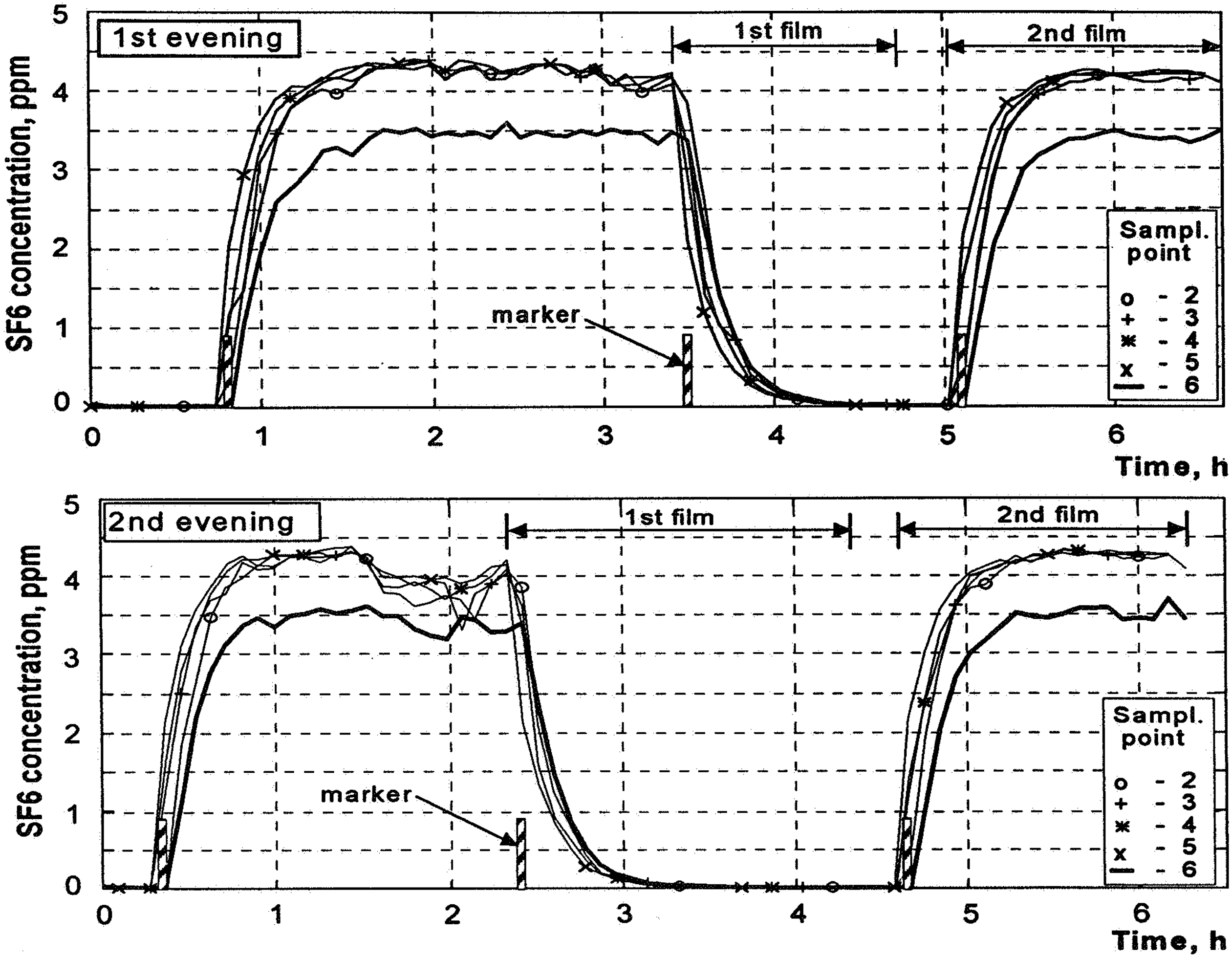


Figure 5. Variations of SF_6 concentration during the step-up and step-down measurement. The actual start time is marked by the marker.

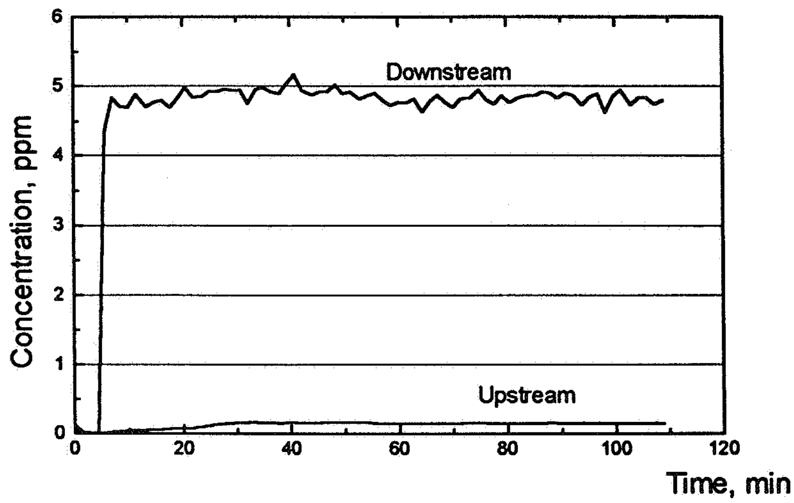


Figure 6. The measured concentration in the upstream and downstream of the dosing point in the supply duct.

The measured air exchange efficiencies are summarised in table 2.

Table 2. The measured air exchange efficiencies.

No. of occupants	1st evening			2nd evening		
	0	2	9	0	22	16
Method	*Step-up*	*Decay*	*Step-up*	*Step-up*	*Decay*	*Step-up*
Local	ε_p			ε_p		
Point 2	54%	52%	53%	56%	46%	55%
Point 3	45%	45%	54%	49%	47%	46%
Point 4	55%	44%	44%	48%	42%	46%
Point 5	47%	39%	43%	44%	38%	45%
Room	ε_a			ε_a		
	53%	50%	52%	52%	48%	53%

We can see that the decay method gave lower air exchange efficiencies than those with the tracer step-up method. The air exchange efficiencies for the room were 2 - 5% lower with the decay method than with the step-up method. This might be due to the fact that no mixing fans were used at the start of the decay. The measured local air exchange efficiencies were found more stable with the decay method than those with the step-up method. However, the mean air exchange efficiencies were equally stable for both the step-up method and the decay method, which is different from the conclusion as given in (8).

The measured air exchange efficiencies with various occupancies were found all to be very close to 50%, which is the air exchange efficiency for perfect mixing. The occupants had little influence on the air exchange efficiency due to the downward mixing ventilation and the large air change rate in the cinema.

4.2. Temperatures and CO_2 concentrations

Figure 7 gives an example of the vertical temperature profiles at the beginning and end of a film. The temperatures in the cinema increased about 1°C due to the heat loads from the occupants, but the temperature gradient remained nearly the same. The temperature difference between the heights 0.5 m and 2.5 m was less than 1°C, which was also true for all the other cases, even when the cinema was unoccupied. This might be explained by the downward mixing ventilation with a high air change rate.

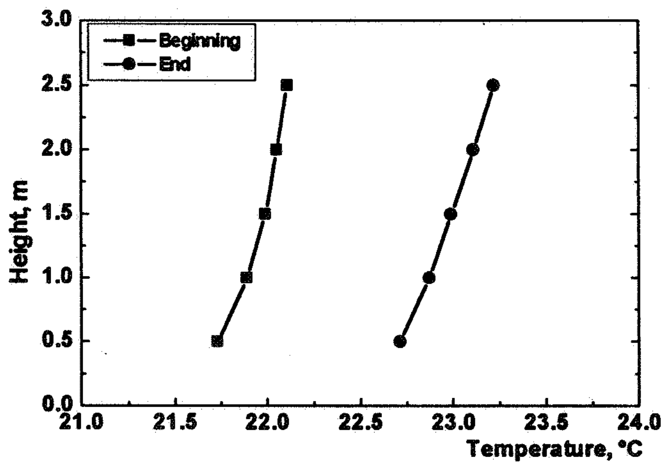
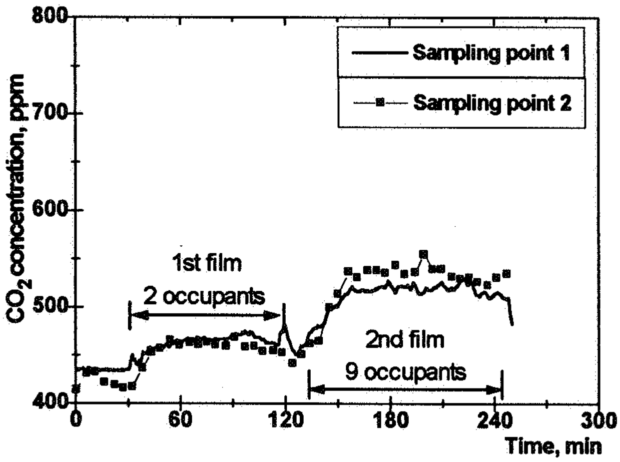
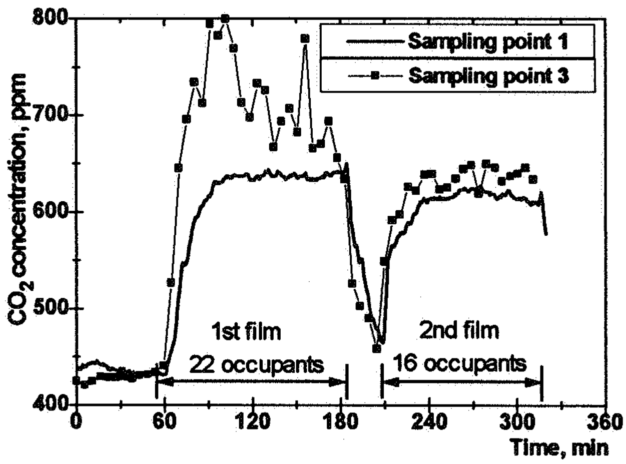


Figure 7. Vertical temperature profiles at the beginning and end of a film with 22 occupants.

Figure 8 shows the variations of CO_2 concentrations at sampling point 1 at a height of 0.4 m and the sampling point with the highest CO_2 concentration among sampling points 2 to 6 at a height of 1.6 m.



(a)



(b)

Figure 8. The variations of CO_2 concentration with time, (a) first evening at sampling points 1 and 2, (b) second evening at sampling points 1 and 3.

There are two possible reasons why the highest concentrations occurred at the sampling point 2 during the first evening and sampling point 3 during the second evening: 1) both of them are located at the back of the cinema below the air supply. As the air was distributed horizontally towards the stage, the CO_2 brought by the convective currents from the occupants might not be diluted directly. 2) the difference in CO_2 concentrations might also depend on the different occupancy densities below these sampling points.

The CO_2 concentration stabilised some 30 minutes after the beginning of the film. The mean values of the increase in CO_2 concentration between 30 minutes after the film began and the end of the film are calculated and plotted against the number of occupants in figure 9.

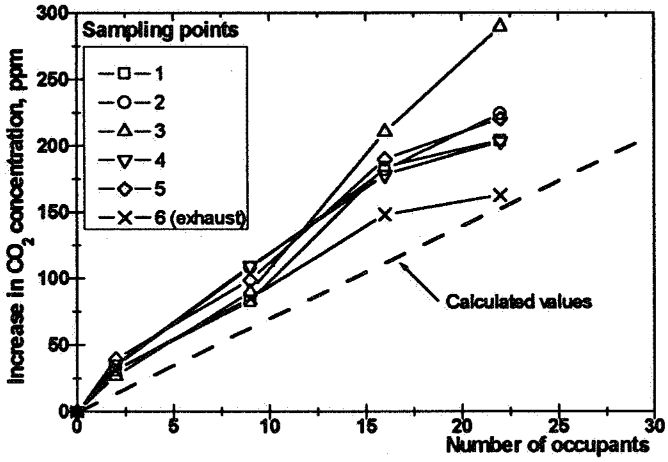


Figure 9. The variations of increase in CO_2 concentration with number of occupants at all the six sampling points. The dashed line represents the calculated values of the mean CO_2 concentration in the cinema at perfect mixing.

As the air exchange efficiencies approach very much that for a perfect mixing, the increase in CO_2 concentrations, ΔC_{CO_2}, can then be estimated by

$$\Delta C_{CO_2} = \frac{n \cdot V_{CO_2}}{q_v} \tag{8}$$

where n is the number of occupants, q_v is the ventilation flow rate, and V_{CO_2} is the CO_2 generation rate per person, which can be calculated using (9)

$$V_{CO_2} = 0.25 \cdot M \ \text{(liter / min)} = 15 \cdot M \ \text{(liter / h)} \tag{9}$$

where M is the metabolism rate, for a sitting person M = 1 met.

The calculated mean increase in CO_2 concentrations are plotted in figure 9.

The CO_2 concentrations were lowest at sampling point 6, which was located at the exhaust. The difference between the CO_2 concentrations are greater with larger number of occupants. At sampling points 2 to 5, the differences in CO_2 concentrations may be explained by the different occupancy densities below these sampling points. As can be seen, the CO_2 concentrations are higher in the occupied zones than the mean in the cinema space.

CONCLUSIONS

The air exchange efficiencies were measured in a cinema with tracer step-up and decay methods alternately. The measured air-exchange efficiencies are close to that for a perfect mixing, with little influence from the occupants. This might be due to the downward mixing ventilation with a large air change rate. The measured air exchange efficiencies with decay method were found 2-5% lower than with the step-up method. Even though the built-up concentrations were stable at the end of the step-up measurement, a mixing fan should still be used to reduce the errors in the coming decay measurement. The decay method gave more stable values than the step-up method for the local air exchange efficiencies. For the room air exchange efficiencies, it seems that both methods were equally stable.

The increases in CO_2 concentrations were found to be linear with the number of occupants. In the occupied zones, the increases were larger than the mean values. The temperature gradients were small due to the mixing type of ventilation.

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