# VENTILATION TECHNOLOGIES IN URBAN AREAS

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# MODELLING INDOOR AIR POLLUTANT CONCENTRATIONS CONSIDERING AIR MIXING CONDITIONS

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# MODELLING INDOOR AIR POLLUTANT CONCENTRATIONS CONSIDERING AIR MIXING CONDITIONS

## SYNOPSIS

Modelling of indoor pollutant concentrations that varies in time can be a useful tool for estimation of the strength of internal sources and sinks. Usually the modelling has been carried out using one zone, i.e. with the assumption that the air is well mixed [1,2,3]. The present paper demonstrates that the methodology may be modified to fit multizone situations.

By studying the decay of a tracer gas, a correct model can be obtained for a specific volume in a building. For each zone in the volume, the model will include one exponential function. Once the correct model is obtained it can be used to determine the strength and the origin of a pollutant source or sink. This method will increase the agreement between the measured and calculated indoor concentration of the pollutant studied.

As pointed out in this paper, the well mixed assumption with one zone can not be used in all buildings. In a specific case, which was created in a test chamber, the total volume had to be divided into three zones, with different airchange rates to achieve a satisfactory agreement with measured data. A two zone model was sufficient to study fast variations in concentration, but to study slow changes a three zone model was needed. A similar situation, like the one created in the test chamber, may arise in buildings in operation when the supply air devices and the exhaust air devices are incorrectly installed and as a result there is a short circuit, which divides the volume into two or more zones with different airchange rates.

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $\dot{V}_{source}$ | internal source strength | cm³/s |
| $\dot{V}_{sink}$ | internal sink effect | cm³/s |
| $\dot{V}$ | airflow rate | m³/s |
| $V$ | volume | m³ |
| $\dot{V}_i$ | airflow rate in zone $i$ | m³/s |
| $\dot{V}_{tot}$ | total airflow rate | m³/s |
| $C_E^n$ | exhaust air concentration at current timestep | ppm |
| $C_E^{n+1}$ | exhaust air concentration at next timestep | ppm |
| $C_S$ | supply air concentration | ppm |
| $C_E$ | exhaust air concentration | ppm |
| $C_{Ei}$ | concentration in zone $i$ | ppm |
| $C_{Ew}$ | weighted exhaust air concentration | ppm |
| $\Delta t$ | timestep | s |
| $j$ | number of zones | |

# 1    INTRODUCTION

Analysing concentration measurements of indoor air pollutants is sometimes difficult. Even if the instruments used are correctly calibrated and the measurement locations are properly selected, the analysis may lead to erroneous conclusions. To facilitate proper analysis, with respect to quantification and location of sources and sinks of various pollutants, the measured concentrations can be interpreted by means of a mathematical model. By inserting continuously monitored outdoor air pollutant concentrations data into a model the indoor concentration vs. time can be calculated, under various assumptions about source and sink effects indoors. In this context, the air mixing within the room or building studied can be expected to be important with respect to the accuracy of the calculation.

Determination of the time constant for the ventilation of a room or a building can be done by performing an airchange rate measurement with a tracer gas. By studying the decay of the tracer gas the airchange rate and time constant can be determined for the volume. One way to determine if the building or room is divided into more than one zone with respect to airchange rate is to supply the tracer gas at a constant rate until the volume has a uniform concentration. When a constant concentration level of tracer gas is reached in the exhaust air, the supply of tracer gas is stopped and the decay will start. The shape of the decay concentration curve in a diagram will reveal whether or not there are several zones in the studied volume with different airchange rates.

Figure (1) shows an airchange rate measurement carried out in an office building using the measurement principle described above. The building is three stories high and has several rooms which are supplied by the same ventilation system.
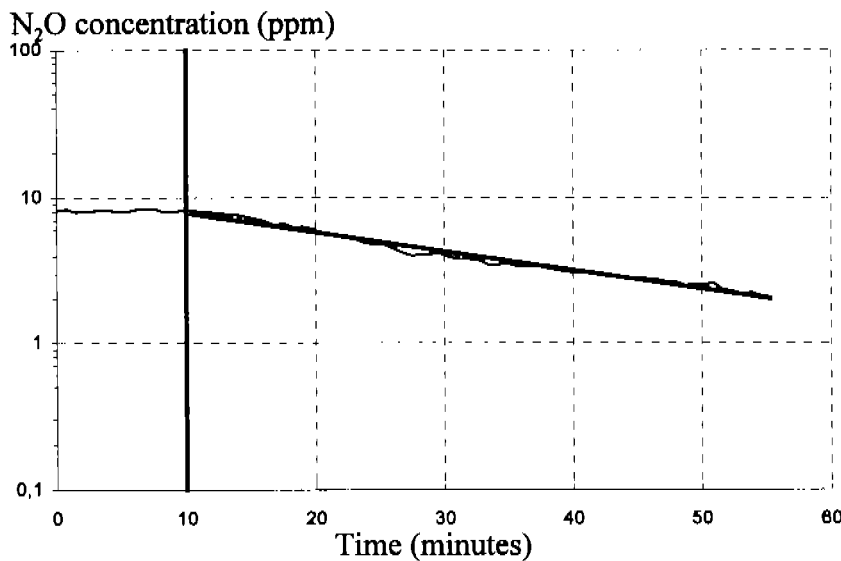
$N_2O$ concentration (ppm)



**Figure 1**    The decay of a tracer gas as a function of time in an office building with a total volume of $4500m^3$. The tracer gas (dinitrogen oxide) was released in the central supply air duct and the concentration of tracer gas was measured in the central exhaust air duct. The supply of tracer gas ends at 10 minutes which starts the decay. The straight line in this line-log diagram indicates that the whole building has almost the same airchange rate. According to this measurement the airchange rate is 1.8 $h^{-1}$.

The tracer gas was released in the central supply air duct of the building and the concentration was measured in the central exhaust air duct. The supply of tracer gas was stopped when the concentration had reached a constant value. The decay is a straight line in the line-log diagram which indicates that the rooms in the office have almost the same airchange rate.

The model used here works under the well mixed assumption, but even when this is not true, the model can be modified to handle volumes not well mixed. The present paper deals with systematic errors that can occur if a multizone situation is not considered. The influence of random errors with respect to airchange rate measurements has previously been presented [4,5,6].

## 2    METHOD

### 2.1    Concentration model

The model is based on equation (1) which is a balance equation. What is supplied to the volume is equal to what is removed.

$$\dot{V} \cdot C_S + \dot{V}_{source} = \dot{V} \cdot C_E + \dot{V}_{sink} + V \cdot \frac{dC_E}{dt} \tag{1}$$

Equation (1) is valid under the assumption that the air is well mixed. The analytical solution to equation (1) is then:

$$C_E(t) = C_S + \frac{\dot{V}_{source} - \dot{V}_{sink}}{\dot{V}} + \left( C_0 - \frac{\dot{V}_{source} - \dot{V}_{sink}}{\dot{V}} - C_S \right) \cdot e^{-\frac{\dot{V}}{V}t} \tag{2}$$

where:        $C_0 = C_E(t = 0)$

When the air in a volume is not well mixed, the model is modified to handle as many zones as needed to make the well mixed assumption true for each of the zones. In this paper the assumption is that the air is well mixed in each zone.

To enable multizone modelling equation (3) can be used. The concentrations for all the zones are added, each weighted with respect to the airflow in each specific zone and the total airflow ratio.

$$C_{Ew} = \sum_{i=1}^{j} \frac{\dot{V}_i}{\dot{V}_{tot}} \cdot C_{Ei} \tag{3}$$

where:        $\dot{V}_{tot} = \sum_{i=1}^{j} \dot{V}_i$

In the context of this paper only one tracer gas is used as a pollutant and released in the supply air. The sink and source effects are never considered which simplifies the calculation.

## 2.2    Experimental procedure

Tracer gas is supplied at a constant rate in the supply air of the volume to be studied until a constant concentration level is reached in the exhaust air of the same volume. A constant concentration level in the exhaust air means that the concentration in the studied volume, for example a room or a building, is uniform. The supply of tracer gas is stopped and the decay starts. If present, a zone with higher airchange rate will reach a lower concentration faster than the rest of the volume. Figure (2) shows a calculation of a decay in a volume with two zones.
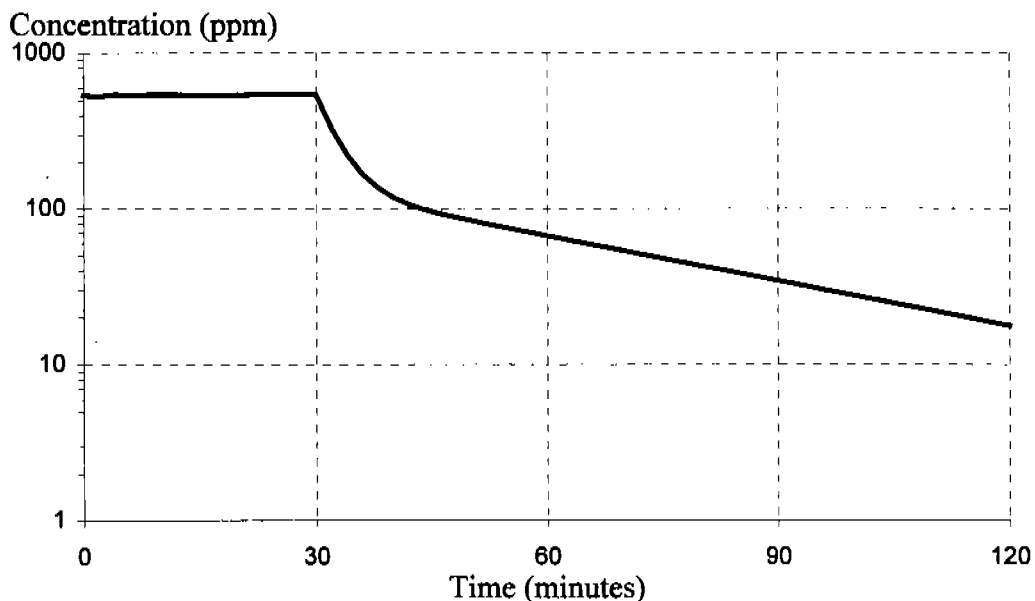


**Figure 2**    Calculated decay of a tracer gas as a function of time. The decay which starts at 30 minutes is calculated with two zones with different airchange rates. The smaller of the two zones has a higher airchange rate, which can be seen as the concentration of the tracer gas decreases fast for a short time in the beginning of the decay. The larger of the two zones has a lower airchange rate and the influence of that zone is dominant in the end of the decay.

A smaller part of the total volume has a higher airchange rate and the concentration decreases faster in that part, and as a result this can be seen as a short but more steep slope in the beginning of the decay curve. The end of the curve is dominated by the larger part of the volume with the lower airchange rate and as a consequence the curve is more flat towards the end. This could be the situation in a ventilated volume with a short circuit in the ventilation system.

In Figure (3) the situation is the opposite with the major part of the volume with a higher airchange rate and a smaller part with a lower airchange rate. The characteristics of the decay curve will also be different with a long steep slope in the beginning and then flattening out just in the end. This could be the situation in a volume which has a zone where the air has stagnated. With these characteristics in mind it is possible to make an estimation of the situation in a volume by just studying the decay curve.
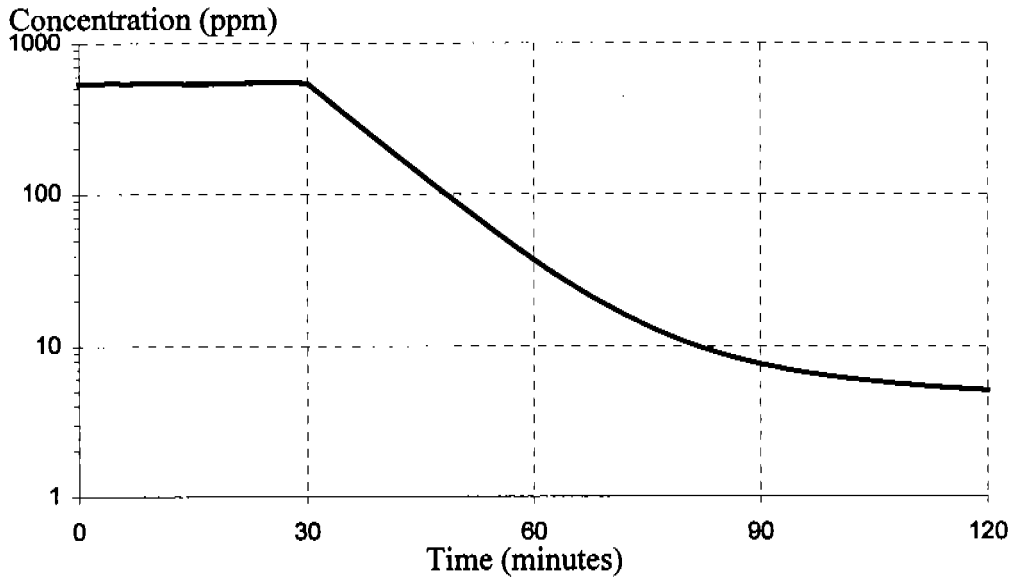
Concentration (ppm)



**Figure 3**      Calculated decay of a tracer gas as a function of time. The decay which starts at 30 minutes is calculated with two zones with different airchange rates. The larger of the two zones has a higher airchange rate. The concentration of the tracer gas decreases fast in the beginning and also for the major part of the decay. The smaller of the two zones has a lower airchange rate and the influence of that zone is dominant just in the end of the decay.

The method described will reveal if there are parts of a volume with different airchange rates. It does, however, not reveal the location of the different zones.

A test chamber with a volume of 19,3 m³ was used to evaluate this method. The supply and exhaust air devices were located close to the ceiling. The supply air devices in the chamber were deliberately removed to reduce the airmixing function. The supply air was heated to 35 °C, which was 15 °C higher than the surrounding temperature of the test chamber, to divide the volume into zones with different temperatures and as a consequence also different airchange rates. Dinitrogen oxide was supplied at a rate of 1,7 cm³/s and the airflow rate was 18,2 l/s. The tracer gas was supplied until the concentration in the exhaust air had reached a constant level, about 93 ppm.

## 3      RESULTS

Figure (4) shows the concentration of tracer gas in the test chamber as a function of time, from equilibrium is reached and two hours of the decay. A two zone model is applied in this case. The characteristics of the decay curve in figure (4) reminds of the curve in figure (2) with a smaller part of the volume with a higher airchange rate. The best result was reached when the calculation was carried out with one zone 15 m³ large and a time constant of approximately 80 minutes and one zone 4 m³ large and a time constant of 4 minutes. The agreement is, however, poor in the end of the decay. This suggests that the first assumption with two zones is not correct.
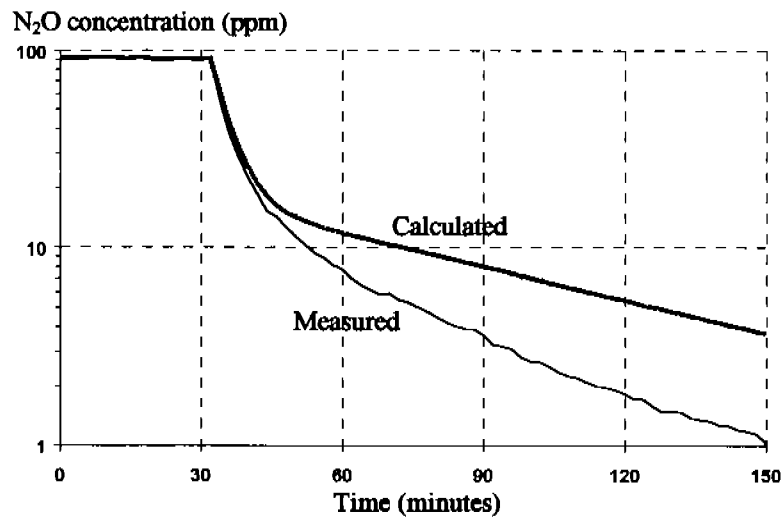
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N₂O concentration (ppm)



**Figure 4**    The measured and calculated decay of dinitrogen oxide as a function of time in a test chamber. The ventilated volume is supplied with 35 °C air and the supply air devices are removed. These conditions force the air to divide into a warmer and more highly ventilated zone and another zone with lower airchange rate. The measured concentration curve indicates a smaller zone with high airchange rate and a larger zone with a lower airchange rate. A two zone model is however inadequate to properly simulate the end of the decay where the agreement is poor.

In Figure (5) the larger zone is divided into two almost equally large zones with different time constants. One of the new two zones has a time constant of 35 minutes and the other has a time constant of 25 hours. A time constant of 25 hours is large, but this could be explained by very slow air movements in the volume in combination with an extreme supply air temperature which creates a zone with almost no airflow. The agreement between the calculated data and measured data is now good all through the decay.
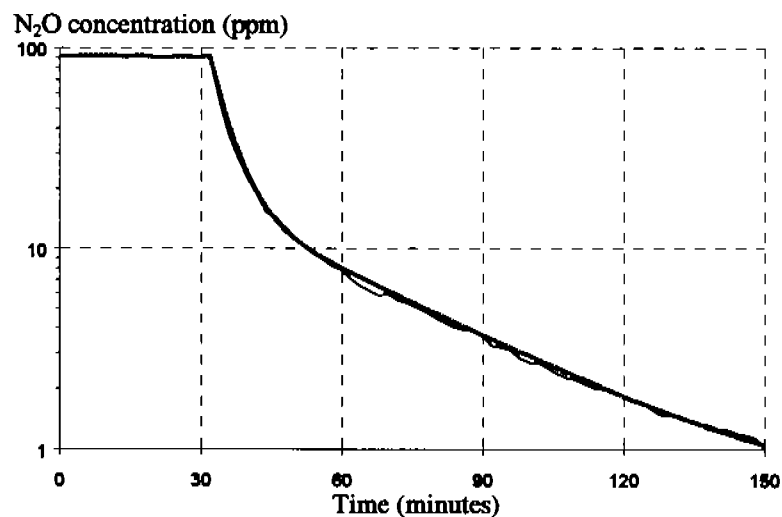
N₂O concentration (ppm)



**Figure 5**    The measured and calculated decay of dinitrogen oxide as a function of time in a test chamber. The measured data are the same as in Figure 4. The model is extended to a three zone model to enable an adequate simulation of the decay.

In order to test the model, tracer gas was pulsed in the supply air. Short pulses of 6 and 4 minutes were used. Figure (6) shows measured and calculated values where tracer gas was pulsed for two 6 minute periods and one 4 minute period, with 6 minutes in between with no supply of tracer gas. The calculation was carried out with same model as that used to calculate the results presented in figure (4).

The agreement between measured and calculated values is good even though the calculation was carried out with a model with two zones. Since the pulses were short the zone with the large time constant could not accumulate enough tracer gas to affect the result. However, if the pulses would have been longer it would have been necessary to use the three zone model used for the calculations presented in figure (5). If the air in the whole volume is considered to be well mixed (one zone), the calculated values differ very much from the measured values which can be seen in figure (7).
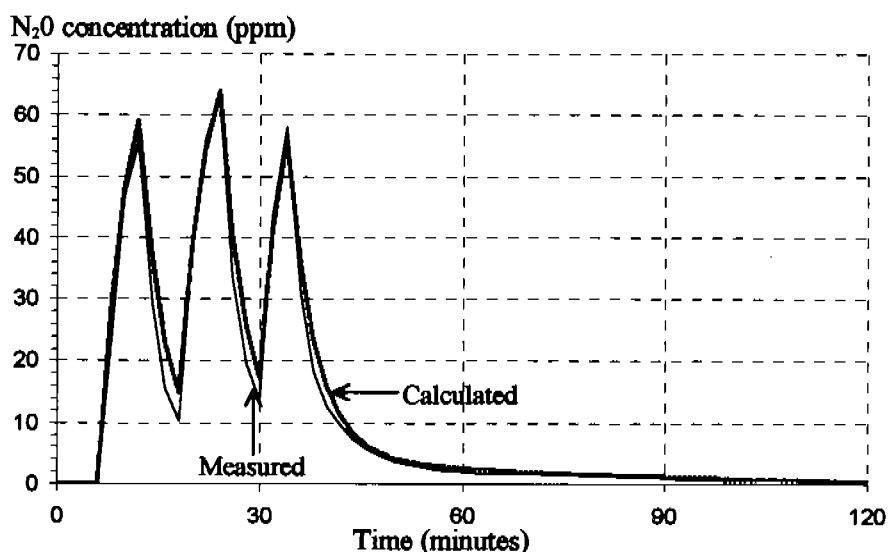


**Figure 6**     Concentration of dinitrogen oxide as a function of time in a test chamber. The tracer gas was pulsed into the supply air, two 6 minute pulses and one 4 minute pulse with 6 minutes in between, and the concentration was measured in the exhaust air. The calculated values were based on the same two zone model used to calculate the results presented in figure (4).

## 4     CONCLUSIONS

The method suggested in this paper will give useful information about the ventilation characteristics for a room or a whole building. This method will increase the agreement between the measured and calculated indoor concentration of the pollutant studied if there is a multizone situation. The method does not give any information about the location of the zones but it will reveal if different zones regarding airchange rate are present.
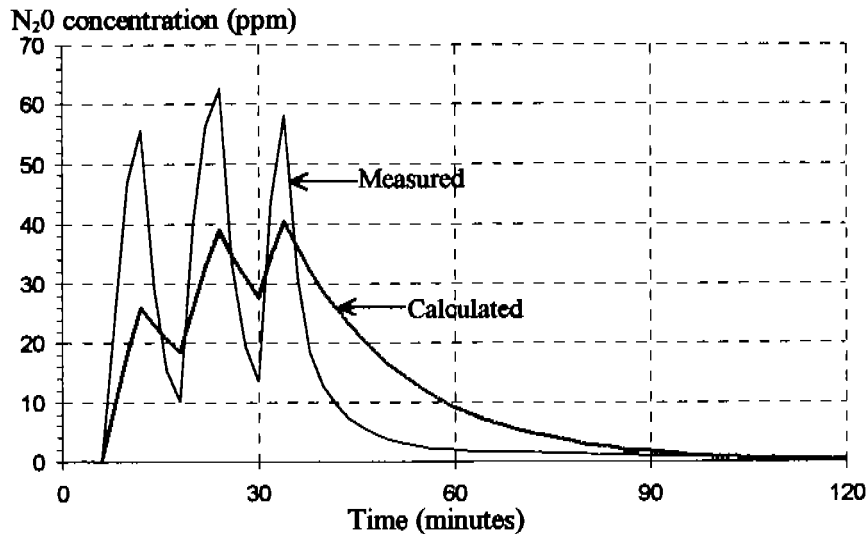
## ACKNOWLEDGEMENTS

**Figure 7**  Concentration of dinitrogen oxide as a function of time in a test chamber. The tracer gas was pulsed into the supply air, two 6 minute pulses and one 4 minute pulse with 6 minutes in between, and the concentration was measured in the exhaust air. The calculated data was based on a model with one zone.

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