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A comparative study of two tracer gases: SF_6 and N_2O

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Abstract

This study compares the characteristics of two tracer gases — sulphur hexafluoride (SF_6), and nitrous oxide (N_2O) — whose densities are different from that of air (i.e. 5.11 and 1.53, respectively). The study is based on exclusively experimental work; and concerns the behaviour of the two gases with regard to their distribution and dispersion in an experimental cell, incorporating into the comparison method an index that is intended to characterise the ventilation of an enclosed space, namely ventilation effectiveness, ϵ_C.

1. Introduction

The aim of this study is to compare the characteristics of two tracer gases, i.e. nitrous oxide (N_2O), whose relative density is 1.53, and sulphur hexafluoride (SF_6), which, with a relative density of 5.11, is considered to be a "heavy" gas.

The study is based on research carried out in an experimental cell (MINIBAT) at INSA de Lyon (France), using a tracer-gas measuring system.

To begin with, the context of our study is set out, giving some general points about air quality, along with the considerations which led to the choice of tracer gases. Then, the experimental apparatus is presented, followed by the results of the experiments and their interpretation. Finally, the choice of a tracer gas for use in the future studies is discussed.

2. The framework of the study

This work, along with the experimental measurements on which it was based, was carried out in the framework of the programme of research undertaken by the Groupe de Pilotage sur la Qualité des Ambiances (GPQA), whose task is to initiate and coordinate work on air quality on a national scale; within this framework, the main types of ventilation system are to be studied experimentally, taking account of different sources of disturbance (heating systems, people, etc.). The objective is to determine the effectiveness of ventilation systems in removing pollutants from an enclosed space.

3. Ventilation, and general points concerning air quality

The function of ventilation is to establish, or to maintain, the conditions of temperature and humidity, and also the levels of dust and gas content, which are compatible with a given level of comfort, whatever the different quantitative contributions made by these factors, and at levels of noise and air movement which are also compatible with this level of comfort. In order to achieve these overall aims, there are several tasks that must be performed, the two main ones being air change and the extraction of pollutants.

Ventilation may be natural, in the sense that it may make use of the natural circulation of air through

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openings in a building as a result of wind or thermal draughts. The effects of natural ventilation may, however, be insufficient or unpredictable; and this is what led to the development of mechanical ventilation for mines and ships, then for certain kinds of factory and, finally, for buildings in the residential and tertiary sectors (offices), with their various requirements in terms of comfort, architectural arrangements and climatic conditions. This kind of mechanical ventilation consists of renewing the air in an enclosed space by the distribution of air from outside, possibly in a mixture with air already present in the interior, and sometimes with filtration.

In order to satisfy life-style demands, more and more air-treatment systems are being produced, for office blocks, conference rooms, shops or dwellings [1].

The two main kinds of ventilation system are those which use displacement and mixing. In the present case, we studied a system of ventilation by mixing. In order to compare the different systems, it was necessary to lay down a certain number of general criteria and concepts (such as that of "ventilation effectiveness"), and also a set of indices for characterising ventilation. These indices take account of the air entering a space, and the air already present there, as well as the distribution of pollutants in the space. In this study, two indices are used: ventilation effectiveness, ϵ_{Ci}, at a given point i, in the experimental cell, and average ventilation effectiveness in the occupancy zone ϵ_{OZ}.

The characteristics of an occupancy zone depend on the geometry of the space in question, and its utilisation. The following configuration is, however, often adopted by default for an office:

- two horizontal planes, situated at 0.10 and 1.80 m from the floor;
- vertical planes at a distance of 0.50 m from the outside and inside walls, and 1.00 m from windows, doors and heaters.

We thus obtain:

$$\epsilon_{\mathrm{Ci}} = \frac{C_e - C_s}{C_i - C_s} \tag{1}$$

$$\epsilon_{\mathrm{Ci}} = \frac{C_e - C_z}{\langle C_{\mathrm{OZ}} \rangle - C_s} \tag{2}$$

where C_e is the pollutant concentration in the extracted air; C_s the pollutant concentration in the supply air; C_i the pollutant concentration in the air at a point i and $\langle C_{\mathrm{OZ}} \rangle$ the average pollutant concentration in the air in the occupancy zone.

The term "ventilation effectiveness" expresses the ventilation system's capacity to evacuate pollutants.

If we take it that the supply air is free of pollutants (i.e. $C_s = 0$), the above equations, (1) and (2), car be written:

$$\epsilon_{\mathrm{Ci}} = \frac{C_e}{C_i} \quad \text{and} \quad \epsilon_{\mathrm{OZ}} = \frac{C_e}{\langle C_{\mathrm{OZ}} \rangle}.$$

The present study was carried out in permanent ı in other words the outlet concentration, C_e, was stant.

In comparing the behaviour of SF_6 and N_2C values of their respective concentrations could n used; a common scale had to be adopted. The lation effectiveness is therefore chosen here as the ameter of comparison. This index would not onl information about ventilation but would also allo two tracer gases to be placed on the same scale, would make it possible to measure differences in behaviour.

4. The experimental apparatus

4.1. The MINIBAT experimental cell

The experiments were carried out in the experi tal cell MINIBAT at INSA de Lyon (France).

This installation comprises two cells: cell 1 an 2 (Fig. 1). Cell 1 is separated by a glass wall fro climatic chamber, whose air-treatment system can duce temperatures of between −10 and 30°C. The mal guard is maintained at a uniform temperatu 20°C, so as to represent adjacent spaces.

The study was carried out exclusively in cell MINIBAT. The measurement purposes are thus ited to this cell's existing ventilation system, whi comprised of a fixed inlet (situated at the centre c cell, and close to the ceiling, towards the side the glass wall is situated), a mobile extraction o and a network of pipes for blowing air into, extracting it from, the cell. The user can set the

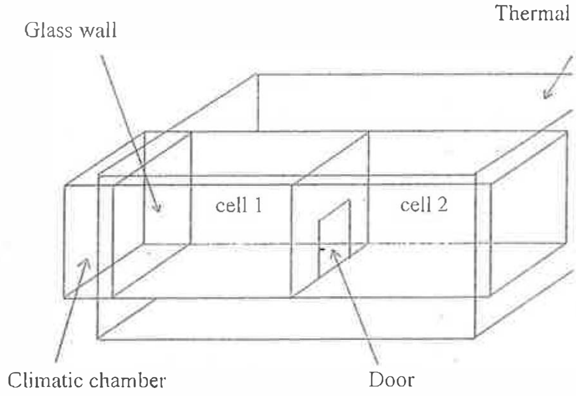

Fig. 1. Diagram of the experimental cell MINIBAT.

temperature at any value between −5 and 35°C; and the inlet and outlet flow rates are also set by the user.

In these experiments, the outlet was positioned directly across from the inlet, on the opposite wall. This is the situation in which the mixing of the air in the experimental cell is least satisfactory (compared with diagonal ventilation); and also, therefore, the one in which there is likely to be the largest difference in dispersion between the two tracer gases being studied (Fig. 2).

The dimensions of the inlet and the outlet are:

- inlet: 0.25 m wide, 0.02 m high;
- outlet: 0.20 m wide, 0.10 m high.

The MINIBAT is equipped with a number or sensors for measuring surface and air temperatures, as well as air speeds and gas concentrations.

Both the cells are also equipped with a device which can be used to move the sensors over their median vertical plane (the plane of symmetry). This device consists of two motors which actuate a metal arm on which is mounted an array of six sensors: two type-K thermocouples for air temperatures, two TSI omnidirectional hot-wire probes for air speeds, and two measuring points for gas concentrations (see Section 5).

All the measurement and collection procedures are controlled by a HP data-acquisition unit and a computer.

The sensor array moves over a 0.10 × 0.10 m mesh grid.

4.2. The tracer-gas measurement method

The tracer-gas technique is the one which is most widely used for studying the movement and quality of air within an enclosed space. Furthermore, procedures using tracer gases are the only ones that can be used experimentally to:

- characterise the ventilation system (with regard to fluxes, flows, etc.); and
- quantify the quality of the air in a space (by determining its age, and studying the migration of pollutants).

This is the method adopted for the present study.

The analyser used in making the measurements was the Brüel & Kjaer type 1302 multigas monitor, whose measurement system is based on the photoacoustic infra-red detection method. This machine can be used to analyse any gas which absorbs infra-red radiation. It uses optical filters (of which the analyser can take up to five) to make individual measurements of the concentration of a maximum of five gases, along with that of water vapour, in a given air sample.

In the present case, the 1302 was used in conjunction with a Brüel & Kjaer type 1303 multipoint sampler and doser; this combination allowed to increase the number of measurement points within the experimental cell.

For more details about the measurement system and operating principles of the Brüel & Kjaer type 1302 and 1303 machines, see [2–4].

In this particular study, gas was injected continuously into the centre of the experimental cell at a

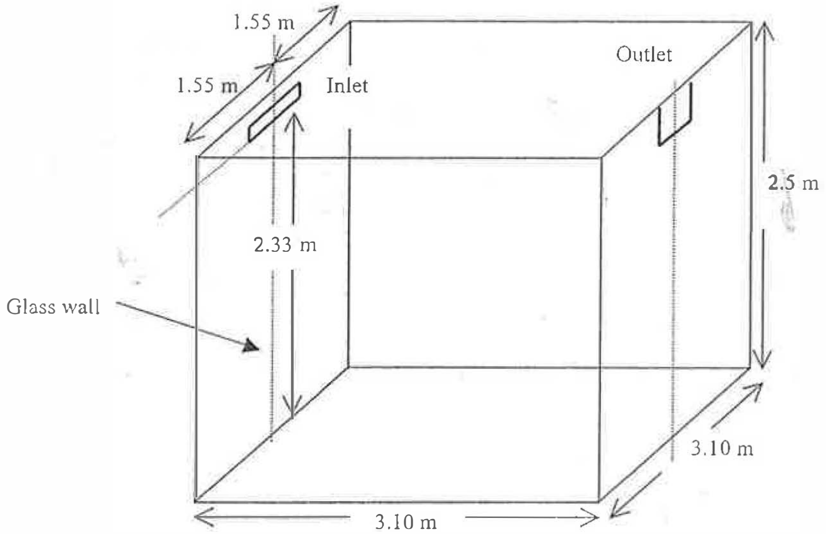

Fig. 2. Positions of the inlet and the outlet — MINIBAT cell 1.

height of 1.20 m. The injection procedure used a table-tennis ball in which a large number of small holes had been made.

There are various ways of injecting a tracer gas into an experimental cell [4], [5], [6], [7], [8], [9], [10], [11], [12], for example:

- the decay method: this consists of injecting a certain quantity of gas into a study volume, and mixing the air until an initial concentration C_0 is obtained; the ventilation system (natural or artificial) is then restarted, and the decline in the concentration is measured continuously;
- the pulse method: a pulse of tracer gas is injected, and the changes in concentration are measured continuously;
- the constant method: the tracer gas is introduced continuously, and at a constant rate, throughout the measurement period. The mixing of the air in the experimental cell should be sufficient to homogenise the concentration of the tracer gas;
- the constant-concentration method: the tracer gas is injected in such a way that its concentration remains constant over time.

The dispersion of the tracer gas in the experimental cell results from a combination of three phenomena:

- movements of the tracer gas itself, by displacement (due to the difference between the molecular weight of the tracer gas and that of the air in the experimental cell);
- the molecular diffusion of the tracer gas in the air within the cell;
- the transport of the tracer gas by the air in the cell, due to convective phenomena.

5. The choice of tracer gas

5.1. The ideal tracer gas

The tracer gases used in studies of ventilation are generally inert, colourless, odourless, and absent from the environment. An ideal tracer gas should possess the following characteristics [5,6]:

- the presence of the tracer gas should not represent any danger for people, materials, or the activities that take place in the space where the measurements are to be carried out;
- for obvious safety reasons, the gas should be neither inflammable, toxic nor explosive;
- the tracer gas should not react either chemically or physically with any other entity that is present during the measurement period and if the reliability of the results is not to be compromised, it must gas which is not absorbed by the walls or furnit does not react on contact with any of the surf or the ambient air, and does not decompose du the measurement operations;
- the molecular weight of the tracer gas shoul possible, be close to that of air;
- the presence of the tracer gas should not inter with the phenomenon being studied, or with the sociated air movements;
- as far as possible, in the interests of precision, ideal tracer gas should be one that is not presen the ambient or external air, even in a highly dil form;
- the tracer gas should be capable of being dete with precision at very low concentrations by chosen instrumentation.

No tracer gas satisfies all these criteria complet Furthermore, a number of other considerations (s as, for example, the cost of the gas and the choic instrumentation) will have an influence on the f choice.

5.2. Existing studies

A number of studies have already been carried to compare the performances of different tracer ga and a selection of these studies is given among the b liographical references at the end of the present art [5,6,10]. In the final analysis, it would seem that th is no gas which stands out clearly from all the oth SF_6 is, however, the one that is most commonly us due to the fact that it is detectable in very small qu tities, and that it is odourless and non-toxic in range of concentrations in which it is generally used.

In thinking about the choice of tracer gas, it is a necessary to take account of the instrumentation av able. The Brüel & Kjaer type 1302 analyser, wh used in this study, is able to determine the conc tration of any gas that absorbs infra-red radiati And N_2O is a gas which satisfies this condition; mo over, its relative density is close to that of air, which a further advantage.

Thus, given the installed system of analysis, and the basis of our literature survey a comparative stu

Table 1
Configurations studied[a]

	T_s °C	T_c °C	Q_s vol/h	Q_e vo
Hot air inlet	34	18	1	1
Cold air inlet	10	26	1	1

[a] T_s, inlet temperature; T_c, climatic chamber temperature; Q_s, fl rate of air at inlet; Q_e, flow rate of air at outlet.

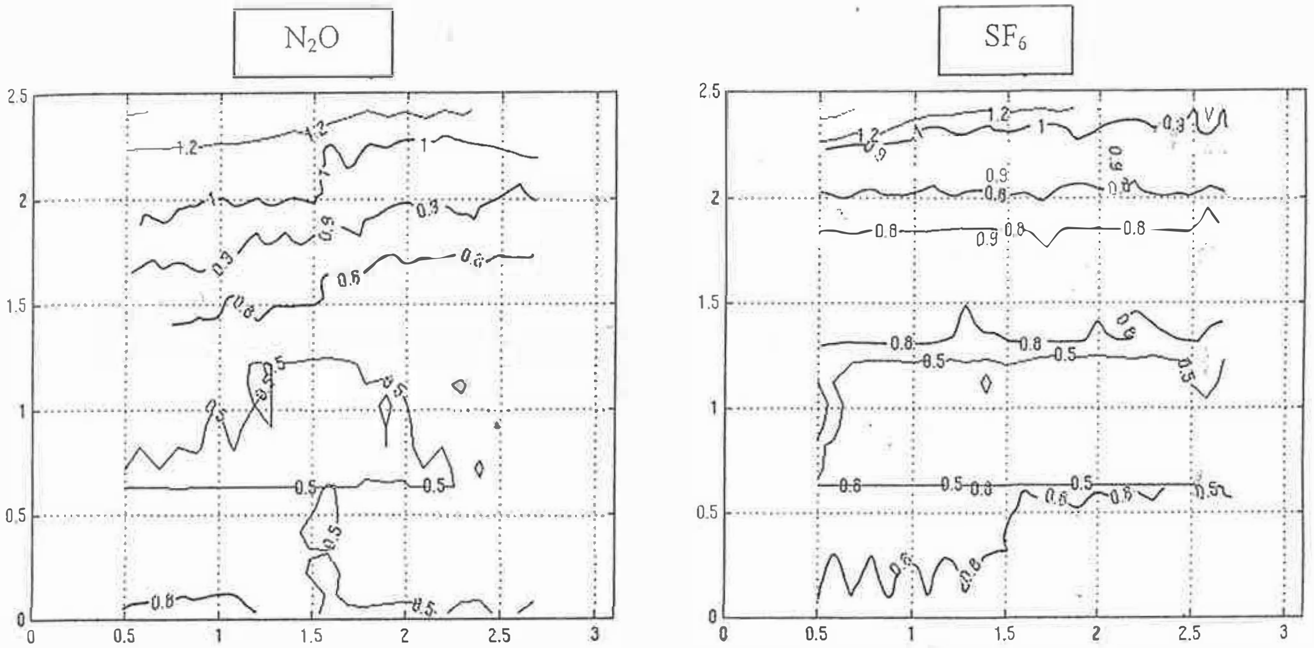

Fig. 3. Iso-ϵ_{Ci} curves — hot-air trials.

of SF_6 and N_2O is opted to do, with a view to deciding which of the two it would be used in the future measurement operations in MINIBAT cell.

6. The experiments

For the experiments, the gas-tracer method discussed above is used. A tracer gas was injected continuously into the centre of the experimental cell at a height of 1.20 m. Trials were carried out with hot air and cold air, and with the two tracer gases, thus providing us, in all, with four sets of experimental results. The different configurations are given in Table 1.

All the experiments were carried out in a monozone, i.e. the MINIBAT cell 1 (which was in contact with the climatic chamber: see Fig. 1). In the different cases studied, the average temperature of the cell was 20°C.

The concentration values were measured at the inlet and the outlet; and the values of the concentration at the outlet and on the median vertical plane were used to determine the ventilation effectiveness values.

The ventilation effectiveness parameter, ϵ_{Ci}, was used to compare the differences in the distribution of concentrations of the gases. The concentration at the outlet was constant, which meant that it could be used as a basis for making comparisons between the concentrations of SF_6 and of N_2O.

From this point on, ventilation effectiveness values will be represented in the form of iso-value curves.

6.1. Hot-air trials

Near the tracer gas injection zone, we obtain:

$$\epsilon_C = \frac{C_e}{C_i} = 0.5 < 1 \Longrightarrow C_e < C_i$$

In this zone there was thus, for both gases, an accumulation of pollutants; but N_2O dispersed better than SF_6, which had a much more pronounced tendency to stratify (Fig. 3).

Apart from the higher degree of stratification shown by the SF_6, the two gases behaved in similar ways. It might be noted that above the tracer-gas injection zone the ventilation effectiveness, ϵ_{Ci}, approached 1 (i.e. $C_e/C_i \leq 1$), while below this zone it was always less than 1, which meant that there was an accumulation of pollutants at floor level. It might be supposed that this phenomenon would have been more pronounced with SF_6 than with N_2O, given that the former is much denser than the latter; but in fact we observed the same level of accumulation with both gases. This can be explained by the fact that the venti-

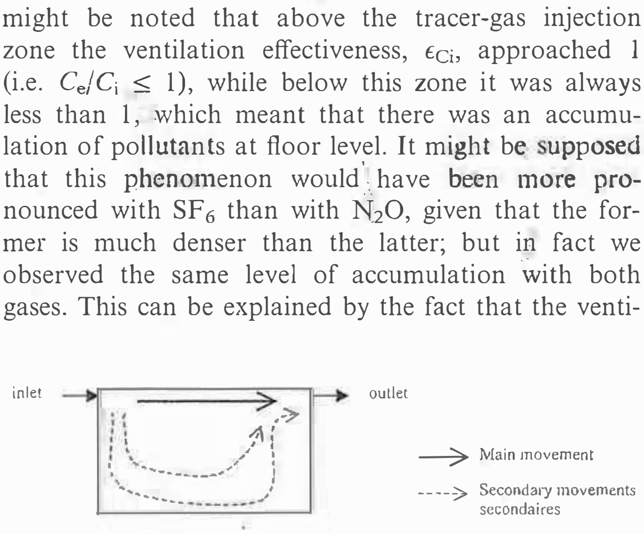

Fig. 4. Air movements in the experimental cell section.

differences between these two gases were not highly significant.

As a result of this study, it has been decided to use SF_6 in the future experiments in MINIBAT. For one thing, N_2O, unlike SF_6, needs a vapour compensation. Also, SF_6 is detectable at very low concentrations, and is not a normal constituent of air; furthermore, it is odourless and non-toxic in the range of concentrations that we generally work with [7]. What can be said is that, at least as far as our chosen experimental conditions are concerned, N_2O, whose relative density is practically the same as that of air, has a tendency to mix and disperse more rapidly than SF_6, with its higher relative density.

One final remark: it is true that, for the experimental conditions used in this study, the measured concentration values could not be taken as a basis for calculating ventilation effectiveness values for the entire occupancy zone, since the median vertical plane (the plane of symmetry), which is where all the measurements were performed, was also where the injection of the tracer gases took place; which means that this area was likely to be more polluted than the rest of the cell. To make up for this drawback, a number of modifications are currently being carried out on the MINIBAT cells, with, notably, the introduction of a second measuring plane, parallel to the original plane; this has been made possible by the installation of a system for moving the sensor array from side to side. The result is that it will be able in the future to obtain information not only on the median vertical plane but also on a lateral vertical plane.

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