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Indoor air flows
A fast-response flame ionization detector for gas concentration

APPLICATION TO THE WIND-TUNNEL STUDY OF INDOOR AIR FLOWS

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Régis Vilagines and Jacques Gandemer, head of the Aerodynamics Department of the CSTB at Nantes, describe the work, within a large research programme, on a measurement system for fluctuating gas concentrations within a small space, based on the detection of hydrocarbons by flame ionization.

René Vilagines et Jacques Gandemer, Chef de la Division Aérodynamique du CSTB à Nantes, décrivent le travail, dans le cadre d'un vaste programme de recherche, d'un système de mesure des concentrations fluctuantes en gaz dans un espace réduit, basé sur la détection des hydrocarbones par ionisation de la flamme.

Introduction

The physics of turbulent dispersion has many important practical implications. It rules the behaviour of contaminants in the atmosphere and acts upon the mechanisms of heat transfer, of fume and dust dispersion, etc. This explains the growing interest in the study of the laws of the turbulent diffusion of passive variables.

Beside the numerical attempts to resolve the equations of some complex flows, a great part of the research work in this domain has been experimental and makes use of facilities like wind-tunnels and water-channels, since full-scale investigations are often impossible or very onerous to carry out.

The simulation at reduced scale of the flows in the atmospheric boundary layer in these test facilities always sets a shorter time-scale to the phenomena reproduced. This implies the need for sensors with a frequency response of several tenths of a Hertz when one wants to examine a natural dispersion process.

The dividing ratio which applies to the time-scale of the flow according to the laws of similitude (Strouhal relationship) is of the same order of magnitude as the geometric scale of the model. In a simulation at scale 1 to 100, suited to buildings aerodynamics studies, the time-scale of the reproduced flow will be of the order of a hundred times smaller than the one at full scale. This means, for example, that a building having a ventilation flow-rate of 1 volume every 10 minutes in given atmospheric conditions will provide a 1:100 scaled model which changes its volume of air in 6 seconds for the same conditions reproduced in a wind-tunnel.

When problems like the impact on the environment of setting up an industrial zone or a chimney, or the energy cost of the air-change in buildings are examined, it is of prime relevance to be able to evaluate the performance and consequently the risks taken, from the stage of the initial project. Experimentation on scaled models in an atmospheric wind-tunnel provides valuable information when the measurements necessary for a good understanding of the phenomena can be performed. Tracers (gases or smokes) are often used to 'mark' the studied flow or to simulate the actual contaminant whose behaviour is under study. Several technologies (light scattering, temperature measurement) allowing the rapid measurement of a scalar variable with a good accuracy, have been developed in recent years and are devoted to various applications (ref. 1). However, there is no sensor commercially available having satisfactory performance from this point of view.

This paper describes a measurement system for fluctuating gas concentration with a small space resolution, based on the detection of hydrocarbons by flame ionization (ref. 2). It has been perfected within the framework of a larger research programme on the ventilation of widely opened built spaces (industrial halls, tropical housing, ventilated spaces behind insulation boardings) and the wind-tunnel modelling of these mechanisms. Elements of the development of this equipment are presented. Some wind-tunnel test results, where the tracer gas decay method was used at small scale to measure air-change rates on a model, are also included.

Description of the system

In essence, a flame ionization detector (FID) consists of a hydrogen-in-air flame burning in an insulated flame chamber, across which a voltage is applied. The introduction of a hydrocarbon gas (ethane, propane,

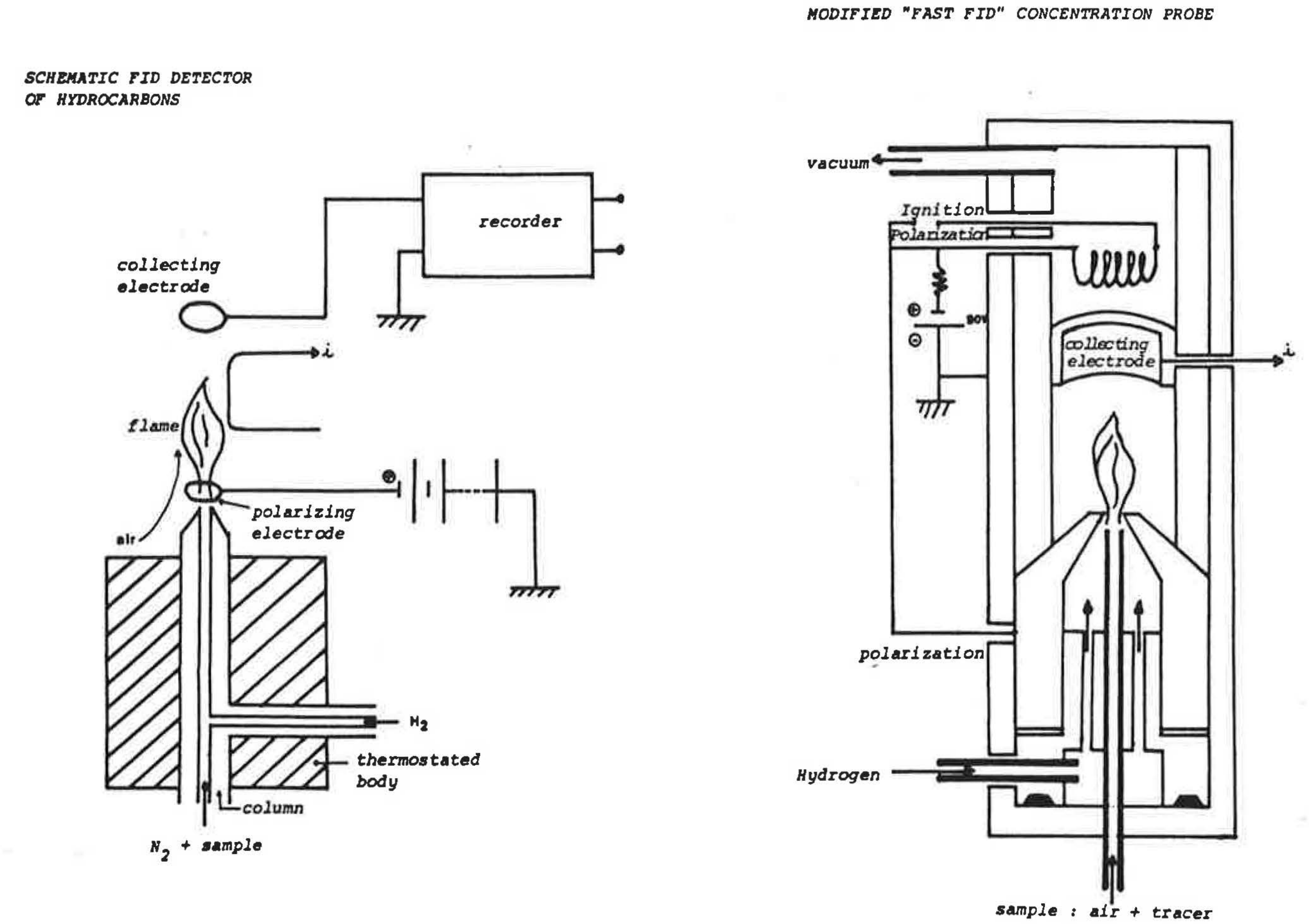


Fig. 1. FID detector and modified probe

ethylene) into the flame leads to the production of ions and hence of a current proportional to the number of hydrocarbon molecules. An electrometer amplifier is used to convert this small current (of the order of 10^{-12} A) to a suitable voltage output. When the sample is introduced into the flame chamber with an appropriate constant flow-rate, the signal obtained becomes a linear function of the concentration.

Available FIDs only allow the measurement of mean concentration and are too voluminous to be used in a wind-tunnel. The two leading ideas of our work were, therefore, to

- modify the flows into the flame chamber to measure fluctuating concentrations
- minimize dimensions to allow wind-tunnel use

The sensor designed at the CSTB makes use of a work by Fackrell (ref. 3), who describes the modifications made to an available FID to enable it to provide fast measurement of the concentration. A special instrument was needed to measure inside the models.

To allow the probe to handle transients and provide continuous measurement of the concentration, the sampled gas is sucked into the probe through a narrow-bore sampling tube (0.8 mm I/D; 0.45 m long) aligned with the axis of the flame, i.e. a jet assembly, where the airflow (with or without hydrocarbons) is centred in the H_2 flow and feeds the flame (Fig. 1).

This central position in the jet is important to obtain a good flame stability and good sensitivity, since the hydrogen uses a part of the air contained in the sampled gas as supporter of the combustion. This arrangement also avoids air feeding from another way.

A flow-meter, placed after the probe on the vacuum pipe, controls the sample flow-rate without modifying the instantaneous concentration. The signal conditioning is mainly performed with a small electronic current-to-voltage converter. Noise on the signal is mainly 50 Hz due to the very high input impedance (1000 MΩ) of the current-to-voltage converter. The noise was lowered down to a value equivalent to ±5 ppm (parts per million in volume) of ethane by placing the converter circuit immediately behind the sensor and carefully screening the ensemble. The voltage output is then carried in a shielded cable out of the wind-tunnel to an additional amplifier.

This layout minimizes the disturbance to the examined flow, since the probe (dimensions: 10 cm × 4 cm) plus its leads are the only parts of the system inside the wind-tunnel. Fig. 2 shows the equipment's layout.

Great care must be taken with the manufacture of the jet assembly, the geometric adjustments and the calibration of the internal pressure losses. The probe must be perfectly air-tight at different temperatures. In the same way, the flow-rates of fuel and sample must be tuned precisely (between 35 and 45 cm^3 of H_2 per minute). More technical details on this type of probe are available in publications on this subject (refs 3 and 4).

Static and dynamic characteristics

The nature of the flow inside the sampling tube and the ratio of Q_{air} to Q_{H_2} determine the performances of the probe.

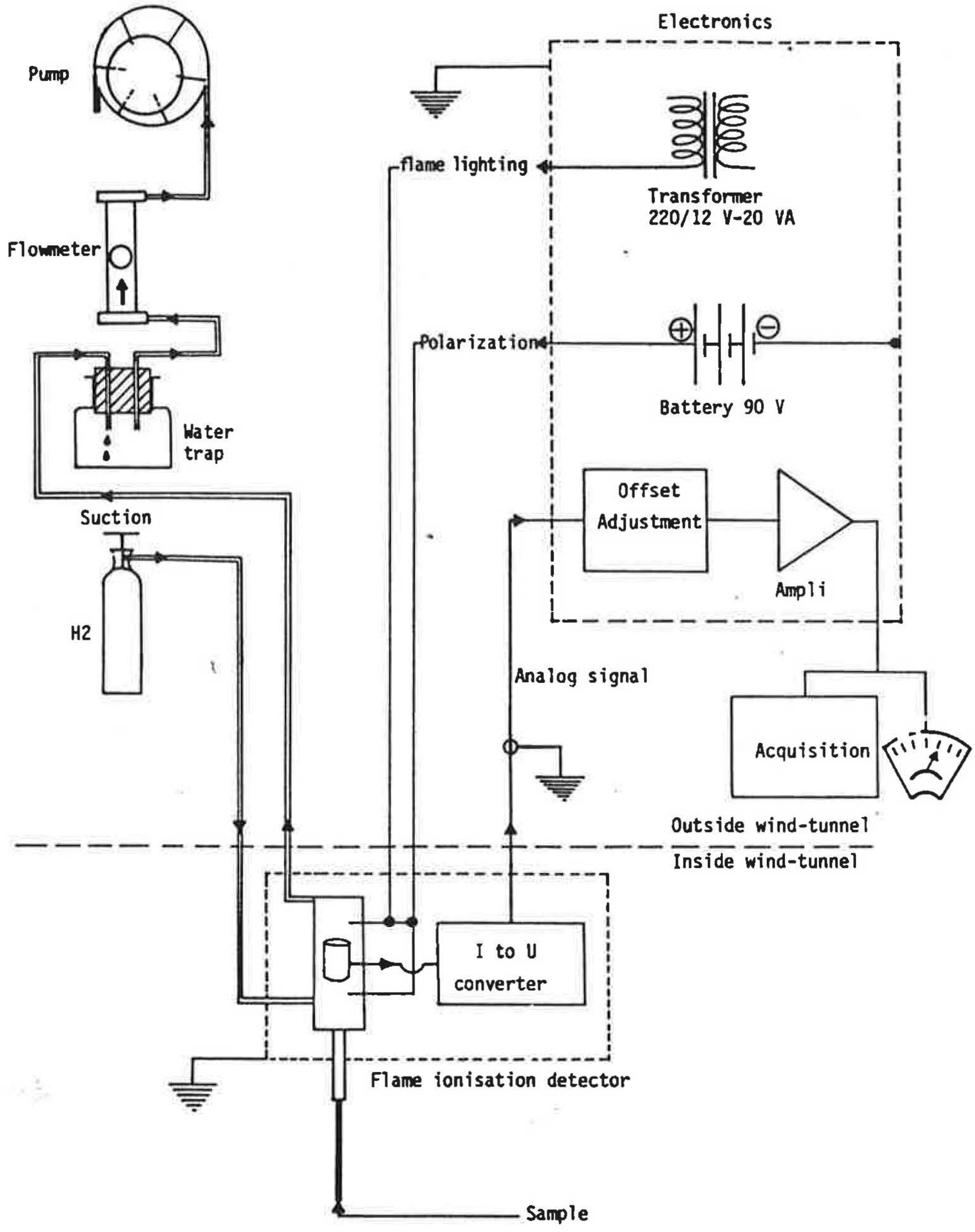


Fig. 2. Fast FID concentration measurement system

The CSTB probe delivers a linear response in the range of some ppmv to 0.1% of ethane.

A few authors (refs 3–5) have proposed analytical calculations of the time-response for this type of probe under some hypothesis. We have chosen to try an experimental estimation of this value for our equipment and compare the measurements with the analytical results.

We refer to the calculation proposed by Fackrell (ref. 3) to determine the amount of dispersion that the sample undergoes when flowing down the sampling tube. The result is directly related to the time response of the probe, if the chemical process of production and collection of ions on the electrode occurs on a negligible time scale. Applying Taylor's theory of longitudinal dispersion of concentration in a laminar pipe flow leads to the following formulation for the frequency response f at -3 dB:

$$f = \frac{0.66}{a}\left(\frac{DU}{L}\right)^{1/2}$$

where D = molecular diffusion coefficient ($D \simeq 18$ mm^2/s), a = internal radius of the pipe, U = mean flow velocity along the pipe and L = length of tube. Although this expression cannot give the exact overall sensor frequency response, it clearly states the weightiness of every design parameter, showing the interest of having a short sampling tube with a small internal diameter.

In addition, two simple experiments have been designed to submit our FID equipment to a step of concentration. The first method was to place the probe tip in a small air–ethane jet and withdraw it suddenly. The second one was to pierce, with the probe tip, a thin paper membrane separating two media of different concentrations. The responses to the concentration steps are recorded and analysed to assess the time response (Fig. 3). Both techniques proved to be efficient and give similar results.

The -3 dB frequency response found experimentally appeared to be higher than the calculated ones for all values of the velocity U tested. For the version of the probe presented ($U \simeq 5.5$ m/s) we measured $f \simeq 43$ Hz whereas

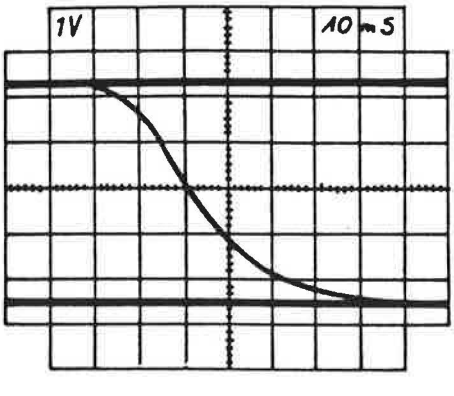


Fig. 3. Example of a probe's response to a step

the analytical calculation yields $f \simeq 26$ Hz. Since the experimental method can only set a lower limit to *f*, the comparison of results suggests care when considering the analytical model.

The spatial resolution *v* of the measurement is associated with the time response τ. Inside the sampling tube, *v* is a cylinder of length $(U\tau)$:

$$v = \pi a^2 U\tau$$

We get $v \simeq 0.1\,\text{cm}^3$ for the case presented.

Additional calibration tests have shown that there is no noticeable influence of the external flow characteristics (direction, velocity, turbulence and temperature) on the probe signal below a velocity of 5 m/s near the sampling point.

Application to the study of indoor air flows

Air change in built spaces is a necessity imposed by a number of criteria like humidity, healthiness and comfort. Furthermore, a major aspect in the thermal behaviour of buildings is associated with the distribution and the flow of the air.

Indoor ventilation can be achieved by means of several techniques, but the air change rate always depends upon the distribution of pressures along the ventilation system. Aerodynamic wind pressures play an important role in this distribution.

Case of natural airflow

Two phenomena generate natural ventilation in a building:

- the wind-induced pressure field
- the 'stack effect'

A pressure difference resulting from an efficient stack effect can be written

$$\Delta P_t \simeq 0.046h(t_i - t_e)$$

where h = height of pipes in metres and $(t_i - t_e)$ = temperature difference between indoors and outside in degrees Celsius. For a five-storey building (h = 13.5 m) with a 15°C temperature difference, we get ΔP_t = 9 Pa for the stack effect.

Moreover, the typical difference between a windward wall and a leeward wall is of the order of

$$\Delta P_v \simeq 0.8\bar{U}^2$$

where $\bar{U}$ is the mean wind speed in m/s. $\bar{U}$ changes with the site, the roughness of the ground, the height etc. However, at say 10 m above ground in an open country site the wind speed exceeds 4 m/s over 50% of the time. For this value, we get $\Delta P_v \simeq 13$ Pa. These orders of magnitude show the importance of the wind in natural ventilation systems.

Case of mechanical ventilation systems

Having regard to the 'effective' pressure differences, much greater than those induced by the stack effect, the wind has a lesser importance though it is non-negligible.

A major difficulty in the study of ventilation problems is the varying nature of the wind. Within the context of ventilation studies, only the average values at the scale of one hour will be considered in estimating mean air-change rates.

Note that the mean air flow rate cannot be obtained strictly from pressure measurements. The flow rate *q* in a ventilation pipe is not a linear function of the discharge coefficient *k* but rather takes the form

$$k = aq^n$$

with *n* ranging from 1 to 2 and often close to 2 (ref. 6). On the other hand, experimental methods using tracer gases can lead directly to the overall flow-rate *q* through any volume *V* (building, room, scaled model in a wind-tunnel, etc).

The next part of this paper is devoted to the adaptation at small scale of one of these methods which enables wind-tunnel study of the ventilation of buildings having high air-change rates, like large industrial halls, tropical housing, atria etc.

Wind-tunnel experimental procedure

The tracer gas decay method

The method is based upon the decreased concentration of a tracer gas injected previously into the volume tested. The evolution of concentration with time is a function of the ventilation flow-rate.

The volume *V* (scaled model for the wind-tunnel experiments or room at full scale) is filled with ethane to an even concentration $C_0 \simeq 1000$ ppmv. During the injection, shutters keep the volume pneumatically isolated from the outside. At time $t = 0$, the shutters are withdrawn suddenly so that the pressure field and the conditions of natural ventilation are restored.

The fluctuations of tracer gas concentration are continuously measured with the 'fast FID' equipment. The signal of concentration versus time is computerized to be processed numerically (Fig. 4).

Data-processing technique

The budget of the tracer gas inside a fixed volume *V* is written at a time *t* as

$$\bar{C}(t) = C_0 + \frac{1}{V}\int_0^t q_{tr}\,dt$$

where $\bar{C}(t)$ = mean concentration in the volume *V* at time *t*, and q_{tr} = volumetric flow-rate of tracer gas *entering V*:

$$q_{tr}(t) = q_{\text{injection}} - q(t)\bar{C}(t)$$

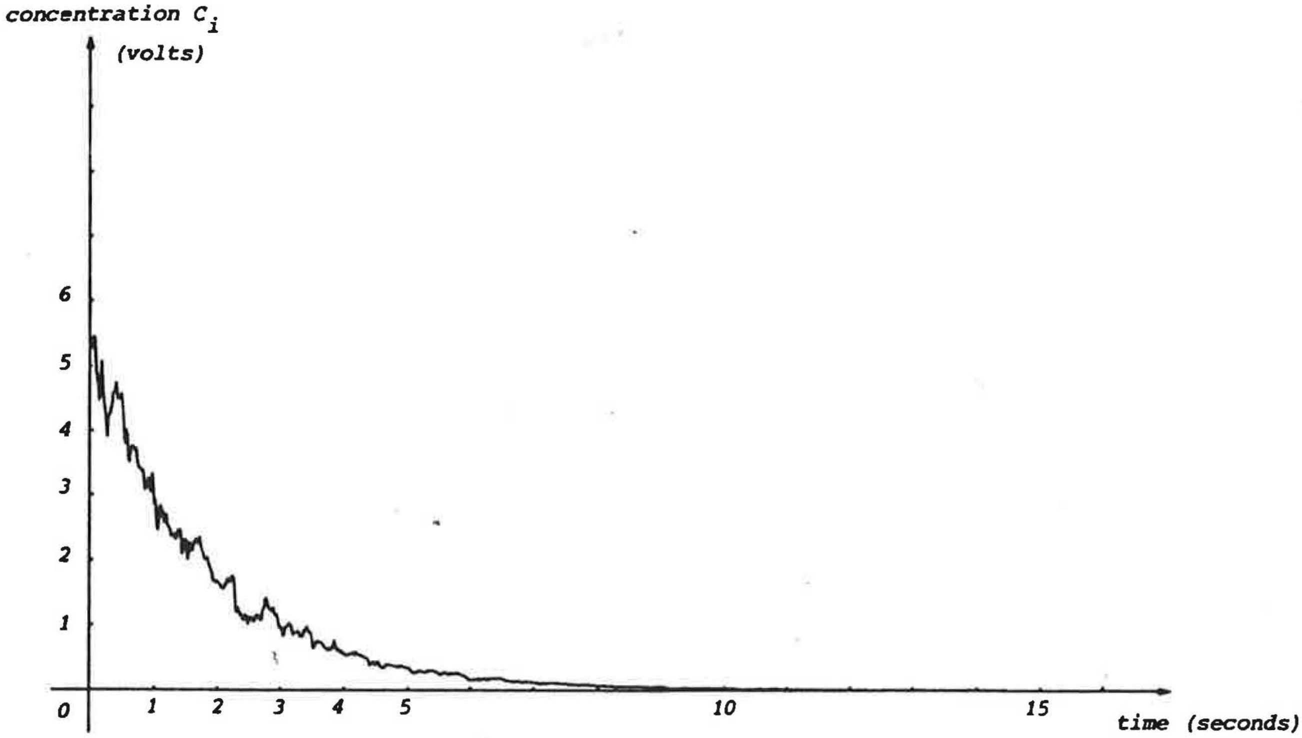


Fig. 4. Example of a curve of concentration decrease in time

The decay method imposes $q_{injection} = 0$ for $t \geqslant 0$. Differentiating,

$$\frac{d\bar{C}(t)}{dt} = -\frac{1}{V}q(t)\,\bar{C}(t) \qquad (1)$$

When the flow inside V is of the type 'continuously mixed' (practical case in many European buildings), the concentration is the same at all locations in V at any time t:

$$C_i(t) = \bar{C}(t) = C(t)$$

for every measurement point i. In addition, when the ventilation flow-rate q is constant (ideal case), Equation (1) can be integrated easily and becomes

$$C(t) = C_0\, e^{-(q/V)t}$$

$\tau = V/q$ will be used hereafter as a definition of the air-change rate of the volume V (in seconds).

In general (strongly ventilated spaces or buildings with complex shapes), only an average value of q is constant (effect of the wind turbulence spectrum). Therefore, it is necessary to mesh the volume and obtain several results at every mesh-point to be able to estimate the average ventilation flow-rate.

Among several methods for calculating τ (ref. 7), the integration is best suited to wind-tunnel measurements. The area under the curve $C(t)/C_0$ is representative of the air-change rate, in the ideal case $\int_0^\infty e^{-t/\tau}\, dt = \tau$). The turbulent fluctuations around the mean exponential decay are automatically 'smoothed' and the computation error is less than 1% for an integration period longer than 5τ (see Fig. 4). The method allies simplicity, rapidity and averaging over the total duration of the measurement.

Wind-tunnel tests

We shall now present some results obtained with the method during a wind-tunnel study of the natural ventilation flows inside a model of a typical single-storey house for humid tropical climates. The order of magnitude of the flow-rates measured puts in evidence the need for the performance of the 'fast FID' concentration measurement system.

Wind-tunnel simulation of natural ventilation flows

The wind-tunnel simulation of natural ventilation flows must satisfy several conditions coming from the dimensional analysis. The correct reproduction of the wind pressure field on the building is achieved only if the static and the dynamic characteristics of the actual wind are reproduced.

When the resulting Reynolds number $Re_{wind\text{-}tunnel}$ lies above a minimum value $Re_{min} \approx 10^5$, it is convenient to choose

$$[\bar{U}(z)]_M = [\bar{U}(z)]_{F.S.}$$

where $\bar{U}(z)$ = mean wind velocity at the height z. The subscript M refers to the model and F.S. refers to the full-scale situation.

In these conditions, the pressure losses occurring in the model will be similar to those at full scale; the ventilation flows will be reproduced correctly and the general expression for the ventilation rate τ simplifies as follows:

$$\tau_{F.S.} = \tau_M \frac{L_{F.S.}}{L_M} \frac{[\bar{U}(z)]_M}{[\bar{U}(z)]_{F.S.}}$$

becomes

$$\tau_{F.S.} = \tau_M \frac{L_{F.S.}}{L_M}$$

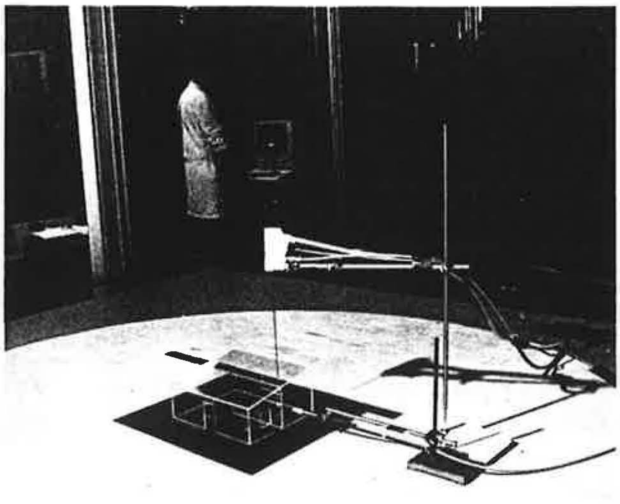


Fig. 5. General view of the model in the wind-tunnel test section

average local air-change rates on the model $\bar{\tau}_{iM}$ (in seconds) are reported beside the measurement points (i) on a top view of the structure tested, together with the corresponding flow-rates $\bar{q}_{iM}$ on the model and $\bar{q}_{iF.S.}$ at full scale. Such a distribution of local results is helpful for further processing.

The height of the points (i) is h_M = 5 cm, i.e. 1.5 m at full scale. A sketch of the structure with its openings is shown in Fig. 6. Fig. 7 shows typical local concentration curves $y = C_i(t)$ obtained by the decay method. In parallel with these results, Fig. 8 gives the horizontal mean flow velocities at the points (i), measured with laser–Doppler velocimetry and the flow structure in the plane of these points, visualized with the laser-sheet technique; the reference windspeed was $\bar{U}_{ref}$ = 5 m/s at $h_{F.S.}$ = 10 m.

Note the values of $\bar{q}_{iM}$ above 3000 volumes per hour at some points i. This corresponds to a 99% dilution of the tracer after less than 5 s, and may go with significant differences between the local results at two close locations that the measurement system must be able to detect.

The wind-tunnel measurement on a model allows direct access to the air-change rate of the actual building on its future site of erection.

In the following example, the reference wind-speed is 5 m/s at 10 m above ground (equivalent full scale), upstream of the 1 to 30 scaled model. The wind reproduced corresponds to the erection of a house in the open country or at the seaside (Fig. 5).

Test results

The results concerning one incidence of wind (the door facing leeward) are presented to illustrate the method. The

Interpretation of results

A separation of the total volume V into two 'sub-volumes' is noticeable when considering the above distribution of local mean air-change rates $\bar{\tau}_i$ and the visualization of the flow structures. This separation is situated approximately in the vertical plane of the internal dividing wall. Inside these two 'sub-volumes' V_1 and V_2 (Fig. 7b) the local results show little difference at two distinct average levels.

Such a flow organization into more or less distinct 'sub-volumes' V_n existed in all the ventilation model studies carried out with the method. This suggests an extension of the notion of 'effective volume' of ventilation, where mixing

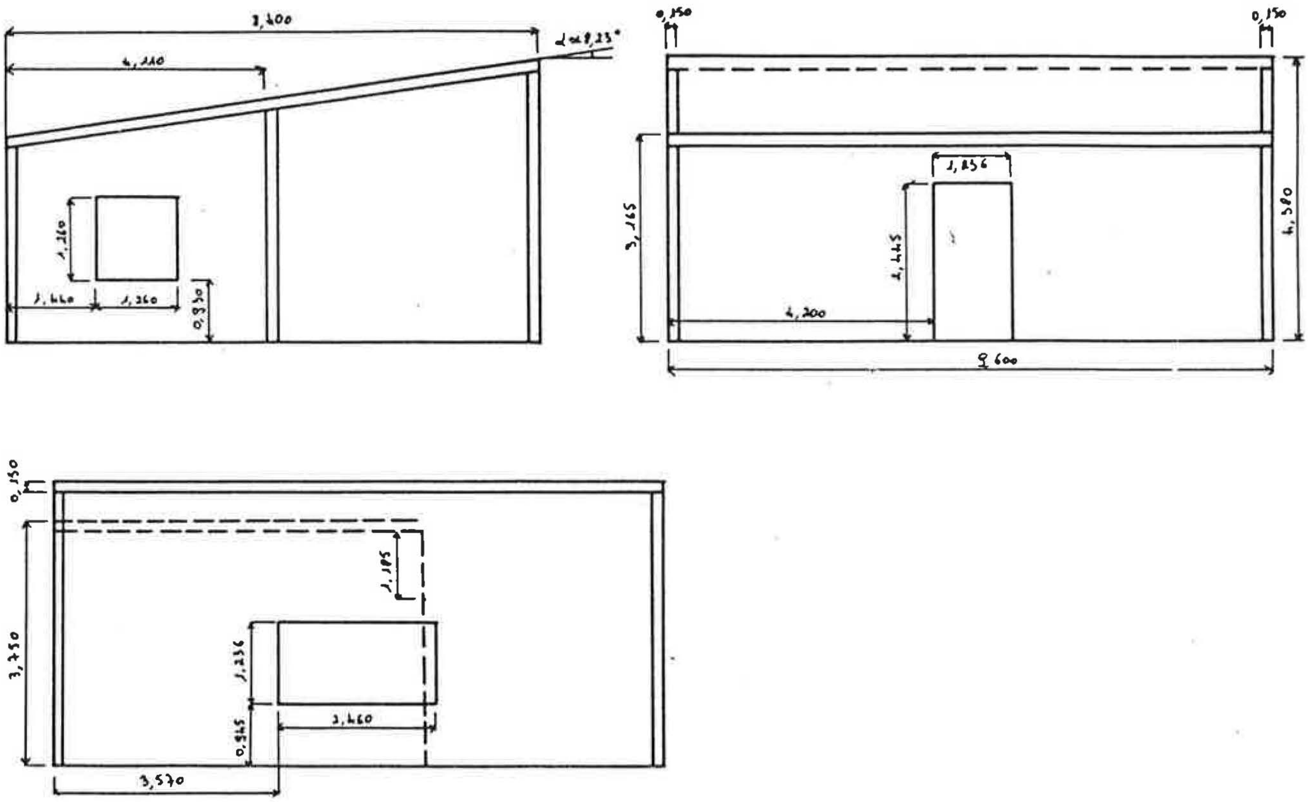
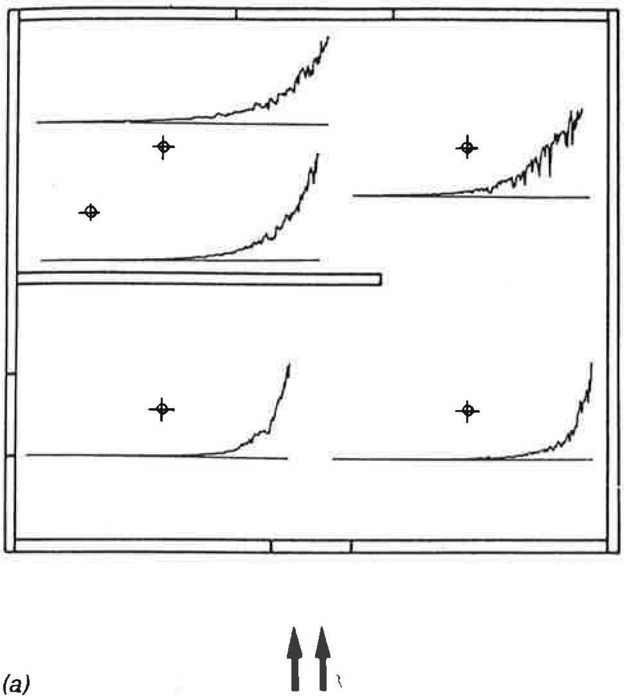
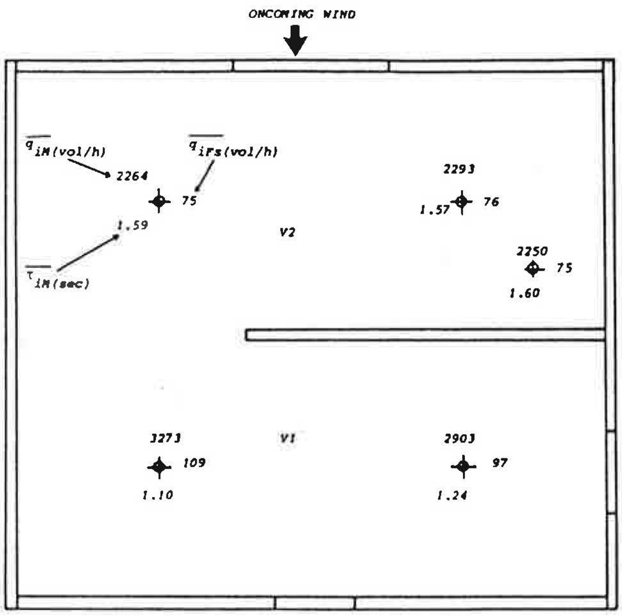


Fig. 6. Three views of the house tested showing openings and dimensions: side (top left), front (top right) and rear (bottom left)

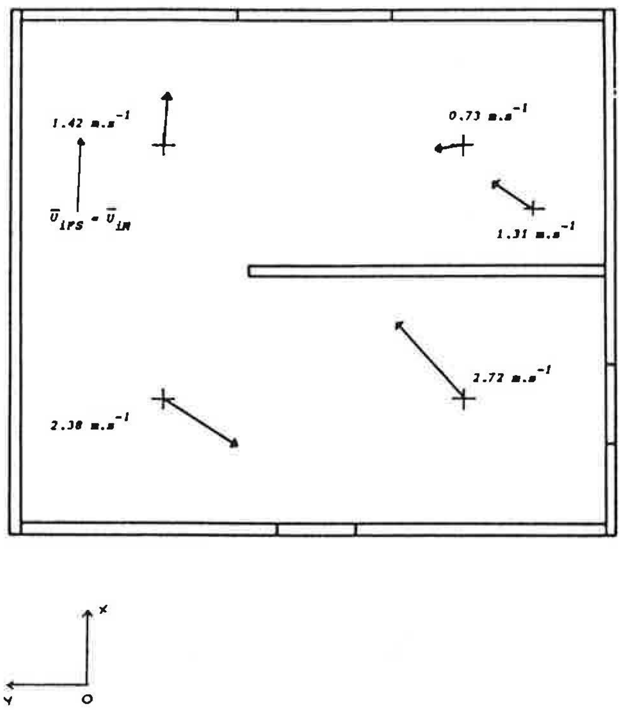


(a)

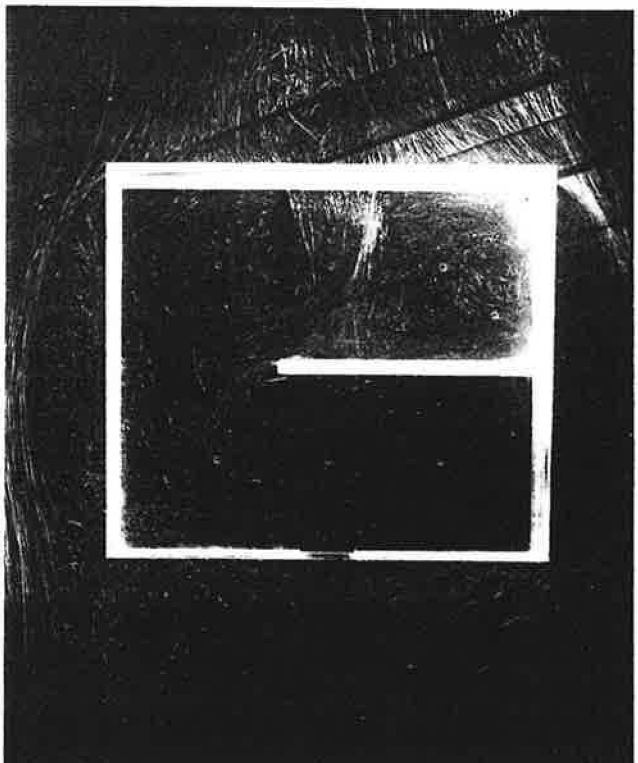


(b)

Fig. 7. Top view of the house with (a) local concentration curves obtained with the decay method and (b) values of the parameters



(a)



(b)

Fig. 8. (a) Wind-tunnel results and (b) flow structure by laser-sheet technique

is perfect, developed by several authors (in particular Sherman *et al.*, ref. 8) to the case of largely porous spaces. Consequently, the choice of the number and distribution of measurement points (*i*) can be justified and an average value $\bar{\tau}_n$ for every sub-volume can be proposed, assuming that the effective volumes have the same size as the respective physical sub-volumes V_n.

Finally, the nominal air-change rate τ_v of the total volume will be estimated from

$$\tau_V = \frac{1}{V} \sum_{n=1}^{p} V_n \bar{\tau}_n$$

where p = number of effective volumes, V_n = size of the effective volume n (in m^3) and V = total volume;

$$V \sum_{n=1}^{p} V_n$$

Here the calculations of the V_n are straightforward; their values are at full scale

$V_1 \simeq 120\ \mathrm{m}^3$

$V_2 \simeq 142\ \mathrm{m}^3$

The resulting full-scale nominal ventilation flow rate is

$q_v \simeq 88$ volumes per hour

In practice, the geometries of the V_n are often more complex and a quantitative approach must be prepared with extensive flow visualizations in regard to the questions of effective volumes sizes, flow stratification, recirculating flows etc.

From the point of view of the study of ventilation streams in tropical flats and houses, the measurement of local air velocities brings additional information. A knowledge of the local velocities is useful for the evaluation of the human comfort level at various locations in the occupied zones (thermal comfort, evaporation of sweat from the skin etc.) (ref. 9), whereas the knowledge of the ventilation flow-rate is useful for calculating the building's thermal budget.

Conclusions

A system for measuring fluctuating gas concentration, offering adequate performance to be used in a number of dispersion experiments in a large wind-tunnel, has been described. Two simple experimental techniques were designed to estimate its frequency response; the result obtained was compared to an analytical calculation.

A practical application has shown that this equipment has characteristics and a reliability which make it an efficient tool, requiring only little attention while in operation.

This instrument makes possible the tranposition, at reduced scale, of the tracer gas *decay method* for measuring air change flow-rates inside wind-ventilated buildings with large openings. In order to allow a systematic approach to these problems on scaled models, a data-processing technique was also proposed.

In conclusion, though its manufacture requires particular attention, the *fast FID* system remains relatively cheap. Moreover, it should be possible to adapt the probe for various conditions of use and thus make the system useful for several domains of experimental research.

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