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SYNOPSIS

So as to better understand and predict IAQ problems, the velocity field and distribution of local mean age of air were determined experimentally with three-dimensional anemometry and decay-mode tracer gas measurements inside a classroom. We also performed 3-D numerical simulations of the velocity field in this room, using a CFD code. The time dependent concentration decay of tracer gas was simulated using the previously determined flow field in the pollutant transport equation. Relatively good agreement was found between the simulated and experimental concentration decay curves. From those curves, a map of local mean age of air was built, allowing us to quantify the ventilation efficiency in the classroom.
Our analyses show that the use of a CFD code to quantify air quality indices and/or to identify indoor air quality issues can be of particular interest for design and diagnostic of sensitive areas with regard to IAQ problems.

LIST OF SYMBOLS

$c_e(t)$	pollutant concentration at exit opening and time t (kg/m^3)
$c_o(t)$	pollutant concentration at supply opening and time t (kg/m^3)
$c_p(t)$	tracer gas concentration at point P and time t (kg/m^3)
k	kinetic energy of turbulence (m^2/s^2)
Q	ventilation rate (m^3/s)
t	time (s)
V	room volume (m^3)
ε	kinetic energy of turbulence dissipation rate (m^2/s^3)
$\varepsilon_{c,p}$	pollutant removal efficiency at point P (dimensionless)
$\tau_n = V / Q$	nominal time constant of the room (s)
τ_p	local mean age of air at point P (s)
$\tau'_p = \tau_p / \tau_n$	normalised local mean age of air at point P (dimensionless)

1. INTRODUCTION

Richalet *et al.* (1994) performed field measurements in 4 classrooms located near Lyon (France) in order to assess the quality of indoor climate and to try to better understand occupants' behaviour regarding windows opening [1]. The survey included measurements of CO_2 concentration, relative humidity, temperature, openings duration, and aerobiological load together with outdoor climate and questionnaires to the occupants. Results have shown very high CO_2 levels coupled with significant aerobiological loads at some time of the day, even in one mechanically ventilated building. In some cases, not only the air exchange rate is insufficient according to the French national standards (that require a ventilation rate of 15 m^3/h per person in classrooms), but also the location of supply and return openings is not appropriate. These observations were in good agreement with the feeling of stuffy climate revealed by the occupants' interviews. From this alarming report, we decided to perform a larger-scale field testing in classrooms in order to better assess the extent of IAQ problems in French schools and in turn, to try to improve the existing situation. In parallel, in this paper, we study the assessment of ventilation systems effectiveness in terms of IAQ. Here, our

investigations focus on experiments performed in one of the previously monitored classrooms (Collège de St Genis Laval, see [1]).
After some background information and a description of our experiments, the fourth and fifth parts of this paper are dedicated to the numerical simulations we performed to predict IAQ indices and dynamic pollutant removal behaviour in this room.

2. BACKGROUND

Literature was reviewed to take a census of the many indices available at present to predict air quality and comfort in a room [2]. It appears that researchers take an increasing interest in IAQ indices such as local mean age of air (τ_p, defined as the average time for air to travel from a supply outlet to point P in a room) and pollutant removal efficiency ($\varepsilon_{c,p} = \frac{c_e - c_o}{c_p - c_o}$) ([3], [4], [5]).
Recently, Gan and Awbi (1994) performed numerical predictions of the local mean age of air in a room using the steady-state approach. To this end, they directly solved the transport equation for the local mean age of air.
They obtained good agreement with experimental data. They also simulated CO_2 emissions generated by occupants and found that the age of air was not appropriate to indicate the air quality in spaces with contaminant sources.

Another limitation of the use of such an index to qualify IAQ lies in the fact that the effect of a given pollutant concentration with respect to health or comfort is essentially non-linear. As a matter of fact, for most pollutants, doubling their concentration or the exposure time does not double their effect on human beings and thus temporal fluctuations of their concentration can have a major impact. As a result, it appears particularly interesting to study the dynamic behaviour of a pollutant concentration.

To this end, we chose to simulate decay-mode tracer gas measurements with a commercially-available CFD code (Fluent) and to compare our results with field measurement data. This way it is possible to compare predicted and measured concentration levels as a function of time and to assess the adequacy of using this CFD code to predict time-dependent pollutant transport. Comparisons between the predicted and measured local mean age of air at different locations in the room were performed using the following equation:

$$\tau_p = \int_0^\infty \frac{c_p(t)}{c_p(0)}\, dt \qquad (1)$$

Thus, local or global pollutant removal efficiencies were assessed numerically. Finally, so as to better understand possible discrepancy in the results, we also performed anemometry measurements with a 3D probe and three omni-directional sensors.

3. EXPERIMENTS

3.1 Description of the classroom

Our experiments were carried out in a full-scale classroom in a secondary school near Lyon (France). The cell studied is shown in figure 1.
The classroom is mechanically ventilated, with the possibility of blowing air at medium or high speed. The inlet air is a mixture of fresh air from outside, heated during the cold season, with polluted return air. Another specificity of the ventilation system in this room is that both air supply and return openings are located on the same vertical wall at the same height. Intuitively,

the existence of a short-circuit of the air flow between supply and return in the upper part of the room, with dead zones in the lower part seems possible, particularly at low inlet air velocities. It is worth noting that our experiments were carried out with the ventilation system turned on maximum speed in order to reach measurable velocities in the classroom.

3.2 Velocity measurements

We performed velocity measurements using 3 hot film omni-directional probes, together with an ultrasonic 3-D sensor. The 3-D sensor acquisition frequency was 80 Hz, the measurement being averaged over the acquisition period. Its accuracy is ± 2 cm/s for velocity magnitude and ± 2° for direction. The omni-directional probes perform continuous acquisition, and give results with an accuracy of ±1.5 % over the range [0 -1 m/s]. A few acquisitions were taken at each location and then averaged.
Simultaneously, air temperature was measured at the inlet incoming jet as well as at several other locations in the room for possible velocity correction. Surface temperatures at walls and windows were measured too. All of these temperature measurements were performed using PT100 probes.

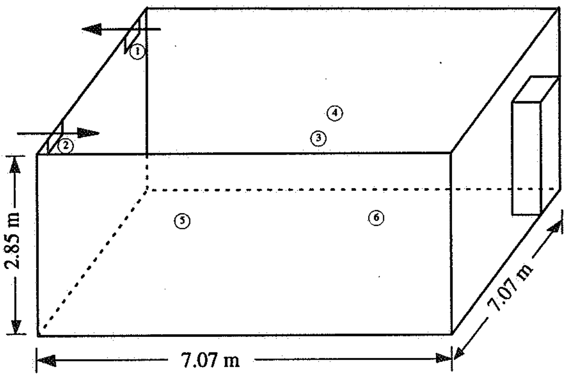


Fig. 1. Classroom dimensions and location of sampling points for tracer gas measurements.

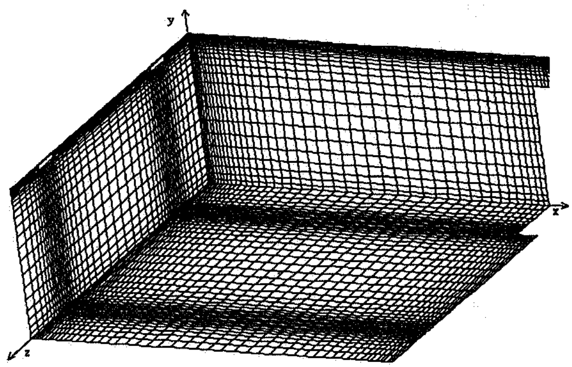


Fig. 2. 3 D computational grid (50 x 26 x 51).

3.3 Tracer gas measurements

To evaluate the distribution of local mean age of air in the room, we carried out a decay mode tracer gas experiment using SF_6. As shown in figure 1, 2 injection points were imposed in the center of the room at a height of 2.70 m. 4 sampling points were distributed over the room (points 4 to 6 at y = 1.20 m, point 3 at y = 2.70 m), and 2 additional sampling points were located at air supply and return so as to evaluate the ventilation system recycling rate. It was found to be 20% with a standard deviation of 2%.
During a first period, SF_6 was injected in the room with all openings sealed, and fans were used to ensure a good mixing. When the tracer gas concentration over the room seemed homogeneous, injection was stopped, fans were turned off, inlet and return openings were unsealed and the ventilation system was turned on maximum speed. Then SF_6 concentration started to decrease, and the experiment was continued until quasi zero concentrations were reached.

4. SIMULATIONS

The finite volume CFD code Fluent version 4.31 was used to solve the non-linear time-averaged Navier-Stokes equation to obtain the flow field in the room. From this converged flow field, the time-dependent transport equation of the tracer gas (here, SF_6) was solved to simulate the decay of the pollutant concentration after injection. The computational grid (51 x 27 x 52 cells) is an irregular cartesian grid with refinement at walls and at air supply and return (fig. 2). Calculations were led using the SIMPLE solution algorithm and the Renormalization Group k-ε turbulence model [6].

Boundary conditions :

- At air supply, a uniform velocity profile at 24°C was applied, deduced from our tracer gas and temperature measurements. Thus, the average supply air speed was set to 1.24 m/s. It is noteworthy that the measured velocity magnitudes near the supply are in good agreement with our tracer gas measurement. However the jet profile, which includes somewhat higher velocities near the center than near the walls of the register was not taken into account. As for the velocity direction, it was deduced from the measured velocity map near the supply register. The supply air jet orientation with respect to the horizontal plane was found to be 27°.
No turbulence characteristics were measured experimentally. However, referring to previous full-scale experimental studies reported in [7], a uniform turbulent intensity profile (10%) was imposed. The turbulence length scale was calculated from the characteristic dimension at the inlet flow equal to the opening hydraulic diameter.
- At walls, a no-slip condition was applied as well as a constant surface temperature of 24°C. Turbulence conditions at walls were the RNG k-ε model built-in conditions for k and ε [6].
- At the flow exit, we set the static pressure to zero.

5. EXPERIMENTAL AND NUMERICAL RESULTS

5.1 Velocity field in the classroom.

Figure 3 illustrates the simulated velocity field obtained at z = 0.67 m, z = 5.64 m, and y = 0.51 m. The flow directions of the numerically predicted velocity field are in general in good agreement with our measurements (see figure 4). However, significant discrepancy in the results can be observed at some locations (see figure 5). Velocity magnitudes tend to be somewhat underestimated in the central part of the room (figures 4 to 6). This may be explained by the boundary conditions imposed at flow inlet. As previously mentioned, although the uniform velocity profile set ensures the correct ventilation rate, the peak value of velocity is not taken into account, which can lead to the prediction of lower velocities within the room.

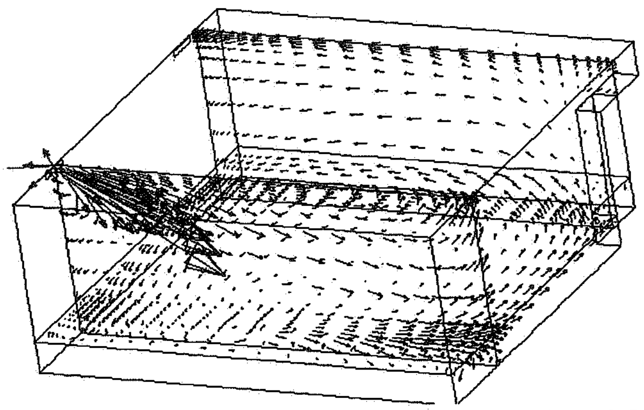
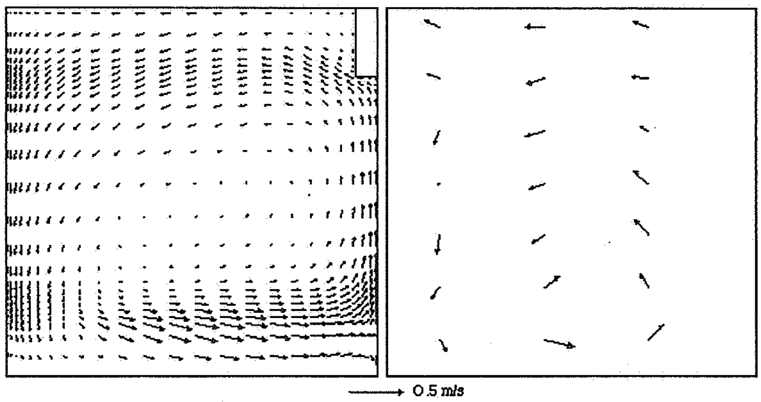
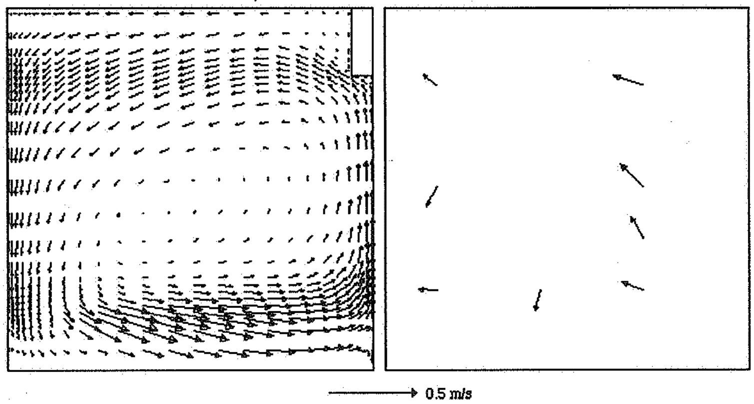


Fig. 3. Velocity vectors at z= 0.67 m, z = 5.64 m, and y = 0.51 m.



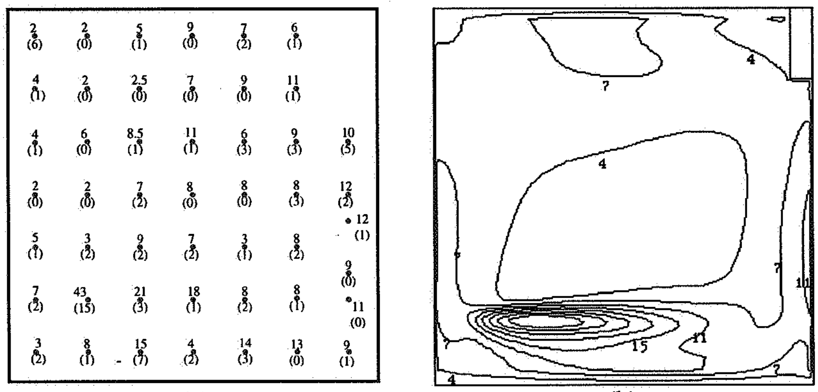
(a) (b)

Fig. 4. Horizontal velocity in a horizontal plane.
(a) Numerical results : z=1.34 m. (b) Experimental results : z= 1.23 m.



(a) (b)

Fig. 5. Horizontal velocity in a horizontal plane.
(a) Numerical results : z=1.59 m. (b) Experimental results : z=1.60 m.

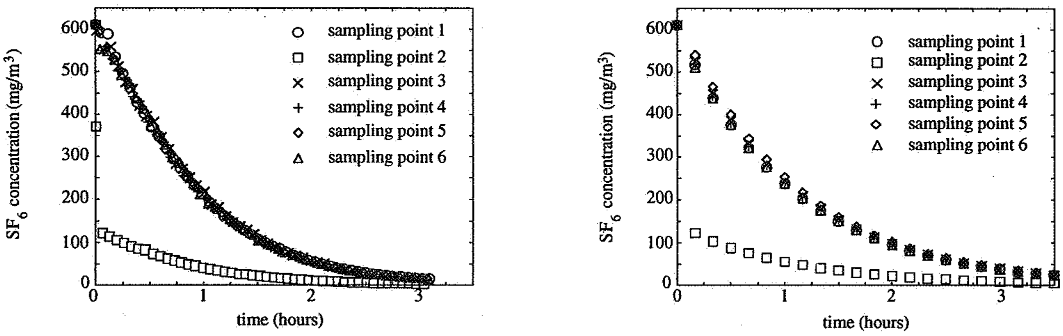


(a) (b)

Fig. 6. Velocity magnitude (cm/s) in a horizontal plane. (a) Experimental results : z=1.80 m. The figure in brackets is the standard deviation. (b) Numerical results : z=1.82 m.

5.2 Air quality in the classroom

From our tracer gas experiment, we observed a great homogeneity of concentration inside the room (figure 7a). It is worthwhile to note that sampling points 4 to 6 were located inside the occupation zone in the room, and so no measurements were performed at corners. As a result, within the occupied zone of this classroom all seats are ventilated with the same efficiency. The reader should note that the ventilation rate set during our experiments (roughly 200 m^3/h) is twice the ventilation rate usually prevailing in the classroom, and that was prevailing during the survey of Richalet *et al.* (1994). Therefore, in the present conditions, it is not surprising that the mixing of air appears better than what we could expect from this previous study [1].



(a) (b)

Fig. 7. SF6 concentration in the classroom. (a) Experimental results. (b) Numerical results.

Predicted concentration decays are displayed in figure 7b. It is noteworthy that the decays are homogeneous (the curves are superposed), which is in agreement with our experimental observations. However, the predicted decontamination of the room appears to be too slow (predicted concentration levels up to 20% more than measured concentrations) (figure 8). One of the explanations of this observed discrepancy lies in the underestimated velocity magnitudes in the room, suggesting that this result could be improved if we better predict the flow field. Also, we can observe in figure 8 that the total amount of tracer gas crossing the return opening slightly differs from its expected value (14 % difference between the areas the concentration decay curves). One explanation lies in the uncertainty associated with the evaluation of the homogenisation concentration (and thus, the initial concentration at the return register) from the 4 sampling points in the room (points 3 to 6 in figure 1).

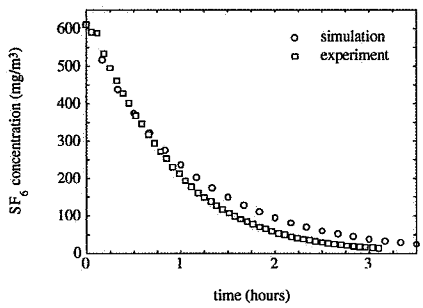
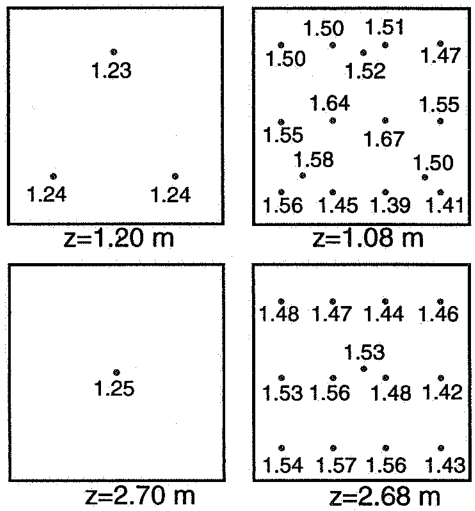


Fig. 8 : Tracer gas concentration at return opening during the decay period



(a) (b)

Fig. 9 : Normalised local mean age of air distribution. (a) Experimental data. (b) Numerical results.

Nevertheless, the numerical results can provide extensive data, and give information about ventilation efficiency at different locations in the room, particularly in terms of local mean age of air distribution (fig. 9).The predicted local mean ages of air, normalised with respect to the nominal time constant of the room, are up to 25% more than those calculated from our experiments. In addition, it can be seen that the experimental age of air field seems uniform in contrast with the predicted results : the variation of the predicted normalised age of air is within 15%.

Moreover, our simulation of concentration decay in a room after injection of a pollutant can give an idea of the way the classroom is decontaminated from occupants pollutant production (CO_2, water vapor) after they leave the classroom, at the end of a class for example.

6. CONCLUSION

From experimental velocity and tracer gas measurements, we were able to estimate the air quality in a classroom in terms of local mean age of air at different location in the room. In addition, we found that the dynamic behaviour of the decontamination of a given pollutant could be simulated with a CFD code, and that the agreement between observed and predicted time-dependent pollutant concentration behaviour is relatively good. As a result, temporal fluctuations of a pollutant concentration can be determined to better assess its impact on man. However, we found that in our case the velocity field that is used to solve the pollutant transport equation is extremely sensitive to the boundary conditions (e.g. airflow direction) at the supply register and it appears that a more detailed modelling of inlet boundary conditions may lead to better agreement with experimental observations. In the future, we plan to focus on this issue and investigate the role of pollutant sources in dynamic concentration levels.

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