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General ventilation characterization

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GENERAL VENTILATION CHARACTERIZATION

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SUMMARY

In this paper, we define some criteria to characterize the local or global efficiency of a general ventilation system. For the local characterization, we suggest to simultaneously use transit time and air renewal rate (or pollutant extraction rate, depending on the fluid which is traced) ; this approach turns out to be more reliable than the internal age one. In the global case, we consider a Flow Model Simulation which allows to characterize the net rate of recirculated fluid inside a room. Recirculation frequency is obtained using a Fourier transform of the local pulse response at the outlet ; it appears that the frequency is partly independent of the measurement point location (it does not need to be located at the outlet). We also study the influence on this frequency of a bad quality of the incoming air tracing.

1. GENERAL INTRODUCTION

In many cases, when a poor extraction of the pollutants emitted in a room is noticed, the question of knowing what is physically responsible for the observed behaviour of fluids arises. The purpose of this paper is to put forward some parameters that characterize pollutant extraction and that lead, provided they are correctly optimized, to a better quality of general ventilation. Two cases can be considered :
- real flows are numerically simulated ; within this context, physical parameters (local concentrations or velocities ...) can be perfectly reproduced from one experiment to the other ;
- measurements are made on real sites or on models ; generally, experiments can be poorly reproduced and some physical features of the flow are not easily detectable.

In this paper, we will only deal with the first case, but some aspects of the second case will be taken into account.

The successive steps of the paper are : first, we begin by defining ventilation principles which, then, are quantified ; we analyse more specifically flow recirculation inside a room ; at last, criteria that have been proposed, are applied in the context of a numerical simulation.

2. VENTILATION CHARACTERIZATION

2.1. INTRODUCTION

Different ways of dealing with general ventilation are communly used. If there is only one area to protect, it is logical to consider it as a priority and, provided that standard deviation of mean values is not too large inside the area, to make it similar to an elementary volume characterized by some local features.

In case the number of sites to be protected represents an important fraction of the total volume, an average approach (of results in each site) prove to be suitable ; we can either perform a spatial average of local features or deduce a global value from a local measurement (located, generally, at the outlet).

2.2. DEFINITION OF SOME PRINCIPLES

2.2.1. LOCAL APPROACH

Local concentration of pollutant emitted in ventilated industrial premises results from the mixing of two flows : one is the pollutant flow and the other the air flow.

The purpose of the ventilation system is to keep the pollutant contamination in working areas as low as possible. The "mixing" approach to ventilation amounts to answer the following questions :
1°/ How is the fluid diluted upstream the measurement point (which is associated with a working area) ?
2°/ How does the flow transfer the matter at the measurement point ?
3°/ What is going to happen to the fluid once the mixing between pollutant and air at the measurement point has been carried out ?

Having this in mind, it is then possible to formulate general principles that should be applied when analyzing a ventilation flow.

For the air flow :
- pure air must rapidly flow towards occupied areas and produce a large local renewal rate of fluid ;

For the pollutant flow:
- the pollutant must come late in working areas to be properly diluted and its local extraction rate must be large enough.

For the mixture flow :
- once the mixture has been extracted from working areas, we have to control that it will not be recirculated back there.

Two parameters can characterize the recirculation :
- its typical **frequency**,
- the **fraction** of the local flow rate which flows back to the working area ; local purging flow rate concept seems to be suitable to deal with this point.

2.2.2. GLOBAL APPROACH

We have to solve the problem of getting an overall information throughout the room from a local information. Some authors proposed a solution within the context of optimization of mixing in a stirred tank (1,2). Then, the approach has been adapted for the case of ventilation and major efficiencies have been introduced to characterize the overall quality of exchange inside a room (3,4,5). But, as fluid recirculation inside a room is concerned, little information is available on the subject ; nevertheless, recirculation is a powerful process of spoiling pollutant extraction. That is the reason why we must, in a first step, detect such a recirculation and, in a second step, quantify it. In the same way we dealt with local recirculation, overall one will be characterized by f_R (typical recirculation frequency) and α (fraction of the total extracted flow rate which is involved in recirculation). To decrease the influence of mixing generated by recirculation, we have to respect the following conditions :

- f_R is small compared with a nominal frequency ($\frac{1}{\tau_n}$ for instance, where $\tau_n = \frac{V}{Q}$, V : volume of the room, Q : extracted flow rate),
- α is as close as possible to 0.

2.3. QUANTITATIVE ANALYSIS

2.3.1. LOCAL CHARACTERIZATION

In this section we shall present a quantitative formulation of the above principles. We shall start from the local age and reexpress it as a combination of two parameters directly connected to our two first principles. We shall show that in some cases the local age concept can be misleading.

Local ages are computed from the local response to a tracer pulse emission at the inlet (3). A pulse response (Fig. 1.) can be splitted into two parts :

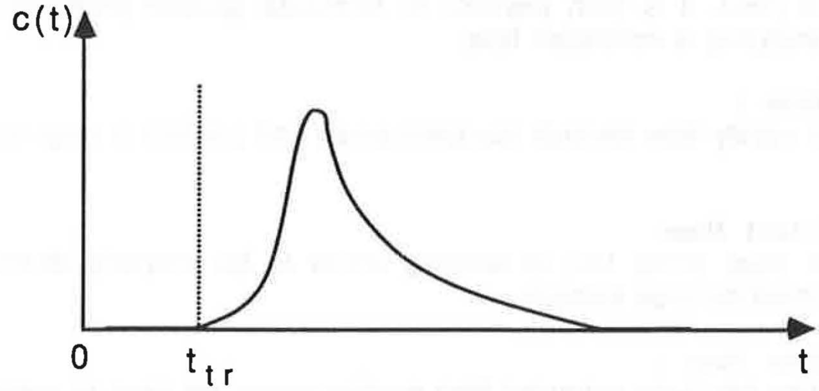


Fig. 1. Pulse response

- up to t_{tr}, there is a nil concentration ; t_{tr} represents the time which is needed by the pulse to be locally felt ; authors agree to call this time "transit time" (6),
- from t_{tr}, concentration increases ; the mean presence time ($\Delta\tau$) of tracer inside measurement volume (or numerical control volume) has the following expression :

$$\Delta\tau = \frac{\int_{t_{tr}}^{\infty} (t-t_{tr})\ c(t)\ dt}{\int_{t_{tr}}^{\infty} c(t)\ dt}$$

The internal age τ_i is given by :

$$\tau_i = \frac{\int_{0}^{\infty} t\ c(t)\ dt}{\int_{0}^{\infty} c(t)\ dt}$$

From that, we deduce :

$$\boxed{\tau_i = t_{tr} + \Delta\tau}$$

In the case of air tracing, puff of tracer comes at the measurement point at t_{tr}. Statistically, it will be evacuated at $t_{tr} + \Delta\tau$. Thus $\frac{1}{\Delta\tau}$ represents air local renewal rate.

In the case of pollutant tracing, $\frac{1}{\Delta\tau}$ represents pollutant local extraction rate.

It appears that the main interest of internal age is that it is the exact sommation of two major ventilation parameters.

What are the consequences on ventilation principles (see **§ 2.2.1.**) if we used those parameters ?

We remind that air must rapidly flow towards working areas and that its renewal rate must be large. That is expressed by :

t_{tr} is small compared with a typical time (τ_n for instance),
$\frac{1}{\Delta\tau}$ is large or $\Delta\tau$ is small compared with a typical time (τ_n for instance).

So, a necessary condition to air behaviour to be favourable consists in having a small internal age.

Regarding pollutant, it must come late in working areas and have a large local extraction rate. That is expressed by :

t_{tr} is large compared with a typical time (τ_n for instance),
$\frac{1}{\Delta\tau}$ is large or $\Delta\tau$ is small compared with a typical time (τ_n for instance).)

Internal age use for pollutant assessment has only a little interest, because one internal age value represents either a favourable or an unfavourable pollutant behaviour. In this case, we think that the best way of evaluating pollutant consists in splitting the pulse response to get t_{tr} and $\frac{1}{\Delta\tau}$.

Remarks :

- Generally, it is not easy to know precisely the instant the pulse response begins to increase. We agree that transit time is the instant the tangent at the first inflexion point cuts the time axis (see Fig.2.).

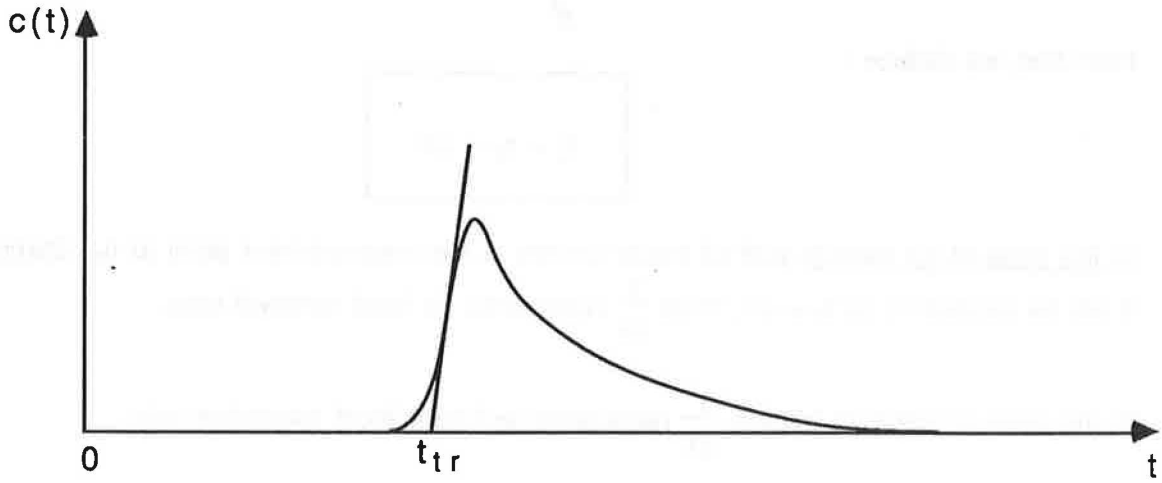


Fig. 2. Time transit calculation

- In case of simulation in real site, it is very difficult to uniformly trace the incoming air (especially if inlet dimensions are large). Furthermore, due to dimensions or position of outlet, local mesurement in it may not be representative of the average extracted fluid. In the global approach, it is sane to wonder if the proposed characterization is still reliable when the incoming fluid is not correctly traced and the outlet measurement point not perfectly located.
  In this paper, we will answer this question only in the case of recirculation characterization.

Going back to the basic principles defined above, we must keep in mind that the fluid dilution is characterized by the **transit time** (t_{tr}) and the mass transfer by **air renewal rate** or **pollutant extraction rate** ($\frac{1}{\Delta\tau}$).

Regarding the third principle, we try to characterize the intensity of what is directly extracted without beeing recirculated inside the measurement volume. Consider that, Zvirin and Shinnar (7) have first introduced local purging flow rate - U_p - ; it represents the net flow rate at which particles of pollutant are transported towards the extract. The smaller U_p

is (compared to the total extracted flow rate), the bigger the recirculated rate of pollutant inside the measurement volume is.

On a numerical point of view, this approach is a very powerful tool. Attractive results have been obtained to characterize the general ventilation (8,9,10). But we have to keep in mind that there is no easy experimental way to get U_p. Because the local purging flow rate is now a well known concept, we will no longer deal with it in this paper. Read (3,9) for further details.

2.3.2. GLOBAL CHARACTERIZATION

We limit ourselves to the characterization of the overall fluid recirculation inside a room by means of two parameters (f_{max} and α, see **§ 2.2.2.**).

To get f_{max}, we simply apply the Fourier tranform to the pulse response and draw its spectrum.

As for α, there is no obvious way to get it ; the local purging flow rate is not suitable in this case : at the outlet U_p=Q (Q : total extracted flow rate) whatever the recirculation degree inside the room.

The approach we propose to calculate α stems from what is used in chemical engineering. Some authors analysed the pulse response at the outlet, and represent a stirred tank considering it as a set of basic models (plug flow, perfect mixing flow...) connected one to the other by means of parallel or serial flows (11,12). Some parameters (relative volume, flow rates, choice and location of the basic flows...) have to be correctly adjusted. This approach will be called Flow Model Simulation (F.M.S.).

We intend to apply this model for our configuration (see Fig. 5.). Because we have, at the moment, no appropriate tool to correctly adjust our model, we impose to have the following (but sensible !) arrangement :

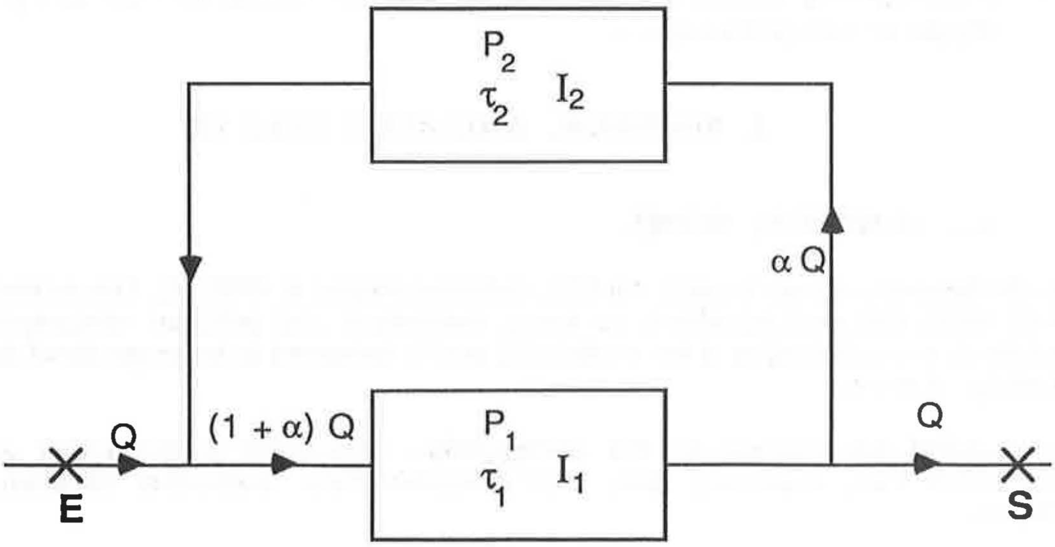


Fig. 3. Flow Model Simulation

The basic flows we take are axial dispersal flows ; their respective pulse responses I_1 and I_2 are :

$$I_i = \frac{1}{2}\tau_i\left(\frac{P_i}{\pi\tau_i t}\right)^{0.5} \exp\left(-\frac{P_i(\tau_i - t)^2}{4\tau_i t}\right)$$

with $P_i = \frac{u_i L_i}{\mathfrak{D}_i}$ (Peclet parameter)

and u_i = mean velocity in the flow

L_i = length of the flow model

$\mathfrak{D}_i$ = mass diffusivity

$u_i L_i = \tau_i$ (12)

We get the contribution R(n,t) of the loop number n to the outlet concentration (point S) by means of the following formula :

$$R(n,t) = \alpha\ F(t) * R(n-1,t)$$

where $F(t) = I_1(t) * I_2(t)$ and $R(0,t) = (1-\alpha)\ I_1(t)$

Thus, the pulse response at the outlet is :

$$c(t) = \sum_{n=0}^{\infty} R(n,t)$$

The model depends on 5 parameters : P_1, P_2, τ_1, τ_2, α. In our case, we are only interesting in having α. The process we followed to get those parameters is :

1°/ calculation of the pulse response c(t) (pulse emitted at E),

2°/ superposing of the numerical pulse response (tracer emission : inlet, measurement : outlet),

3°/ if superposing criteria are not fulfilled, different values for P_1, P_2, τ_1, τ_2, α are chosen and we go back to 1°/.

3. NUMERICAL SIMULATION RESULTS

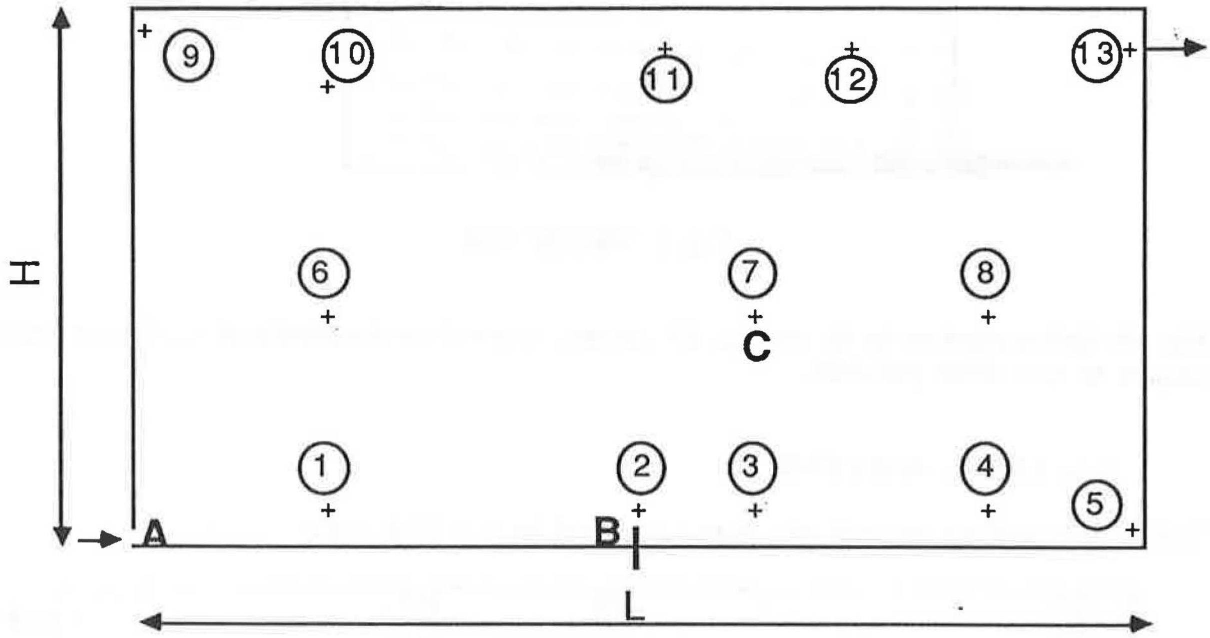
3.1. NUMERICAL MODEL

The computations are done using the EOL-code developped at INRS (8). The numerical model solves mean transport equations for mass, momentum and pollutant concentration. Eddy viscosity is computed using a k-ε model (13) and is supposed to be proportional to the eddy diffusivity of mass.

The physical assumptions for the configuration considered in this paper are : two-dimensional flow, stationary flow, incompressible fluid, isothermal situation, passive pollutant.

3.2. CONFIGURATION

The configuration we used is drawn on Fig.4. Inlet and outlet of air are diametrically opposite. Measurement points (1 to 13) are placed throughout the room and 3 tracer emission locations are considered (A, B, C). Position A allows to uniformly traced the incoming air.



H=0.7 L=1.3 $Re=\rho * U_0 * H/\mu = 20000$ U_0 = inlet velocity

Fig.4. Description of the configuration

For this configuration, the velocity map was calculated :

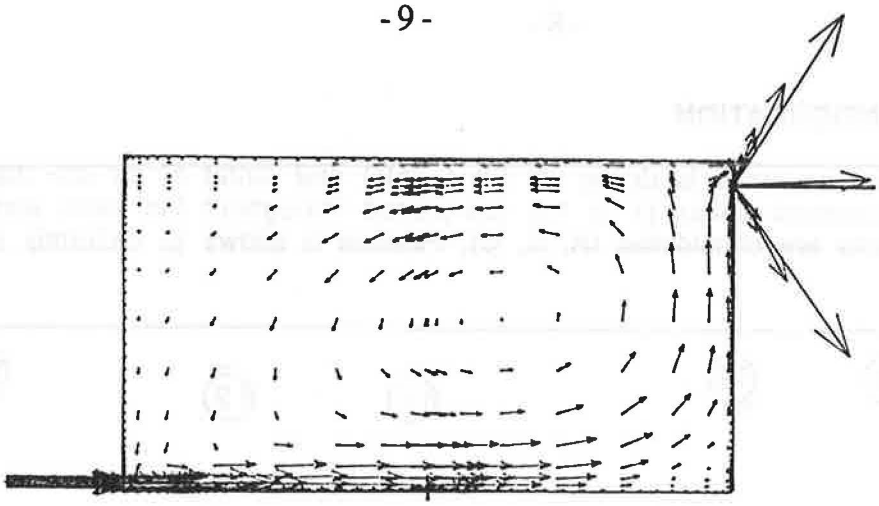
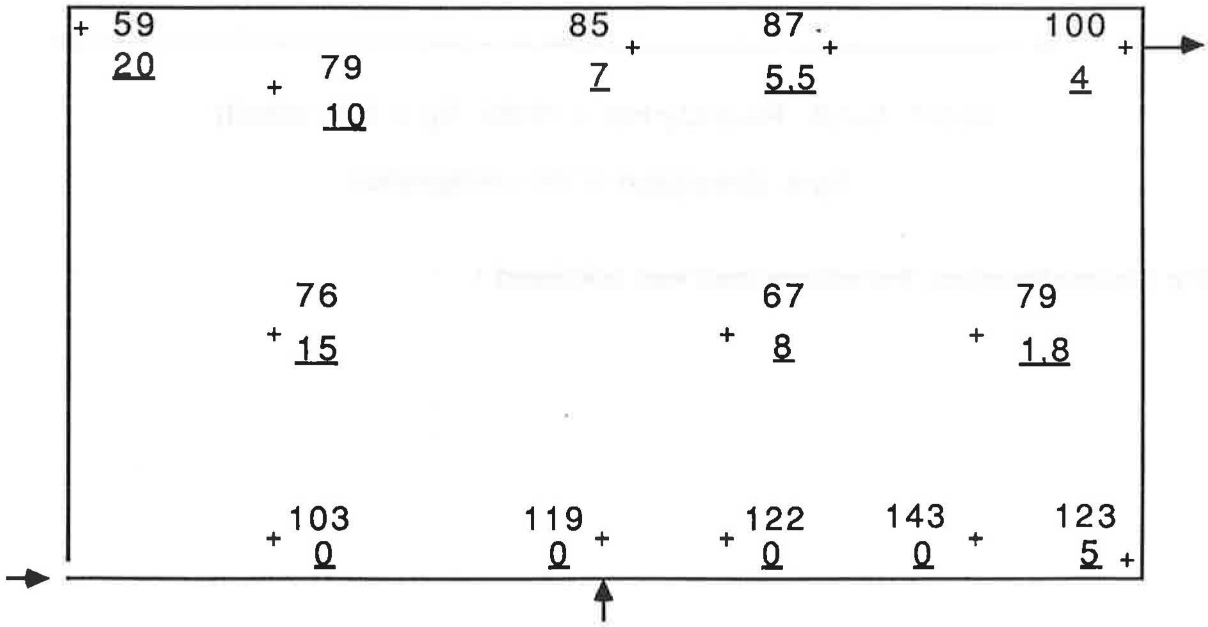


Fig. 5. Velocity field

We will limit ourselves to air tracing. Of course, a complete diagnostic of ventilation would require to also trace pollutant.

3.3. LOCAL ANALYSIS

Transit time and air renewal rate were calculated for the 13 points :



$$\underline{x} = 100 \frac{t_{tr}}{\tau_n} \qquad x = 100 \frac{\frac{1}{\Delta\tau}}{\frac{1}{\tau_n}}$$

Fig. 6. Transit time and air renewal rate

Several regions with specific air behaviour can be found :
- region associated with points 1 to 5
Air behaviour is very favourable, regarding transit time and air renewal rate. However, transit time is relatively large at point 5 : it is to be feared that that air dilution takes place upstream this point.
- region associated with points 8,10, 11, 12 and 13
Transit time and air renewal rate are not as good as in the previous case ; but it is clear that air behaviour is still favourable.
- region associated with pints 6, 7 and 9
We call this region a dead zone, because, on one hand, transit time is large, and, in the other hand, a poor renewal rate is observed.

Remark :
Beware of expressing an opinion when only one criteria is considered ! There is no obvious air stagnation at point 7, for instance, if we only look at its transit time.

3.4. GLOBAL ANALYSIS

3.4.1. CHARACTERISTIC FREQUENCY CALCULATION

A spectral analysis of pulse response at the outlet is performed (Fig. 7, point 13). A peak stands out for f=0.062 s^{-1} (that is to say a characteristic time of 16.1 s) which has the physical meaning of a recirculation periodicity inside the room.

We also wanted to know whether or not this peak appeared when we deviated from an ideal measurement process (see **§ 2.3.2.**). So, spectral analysis was made for different points inside the room (Fig. 7, points 5, 7, 8 and 12) or for different locations of the tracer emission (Fig. 8, tracer emission in B and C).

It appears that the peak frequency does not depend on the point location, provided it stands within the area which is visited by recirculation flow (points 8, 12 and 13). But, if the point is located in an area where local velocities are small (points 5 and 7), peak frequency disappeared. In case of tracer emission in a large velocity area (Fig. 8, tracer emission in B), there is no shift in peak frequency, while no frequency stands out in case of a low velocity tracer emission location (Fig. 8, tracer emission in C).

In conclusion, it turns out to be possible to get the characteristic frequency of a recirculation flow with an imperfect tracing of incoming air and to perform measurement at a point visited by recirculation instead of the outlet.

3.4.2. RECIRCULATED FLOW RATE FRACTION CALCULATION

Criteria we used to adjust Flow Model Simulation and Numerical Simulation (see **§ 2.4.2.**) consists in the superposing of the first two peaks. The proposed model is a convective one and, thus, cannot take into account diffusion of mass inside dead zones ; this process develops very slowly and it is possible to consider that its influence is negligible at the beginning of the response. For small enough times, we think that the model describes correctly mass transport.

In a first step, we studied the outlet pulse response for air tracing. Adjustement of parameters (see Fig. 9-a) gives α = 0.43. In a second step, influence of either a measurement location shift (Fig. 9-b, α = 0.525) or an imperfect air tracing (Fig. 9-c, α = 0.31) was analysed. Contrary to what we got for f_{max}, it appears that the fraction α depends on location of both the measurement point and the tracer emission.

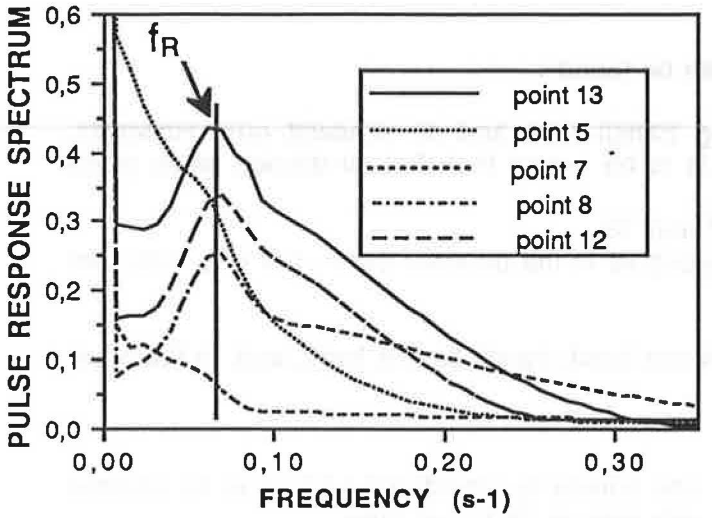


Fig.7. Spectral analysis of the pulse response in different points (tracer emission in A)

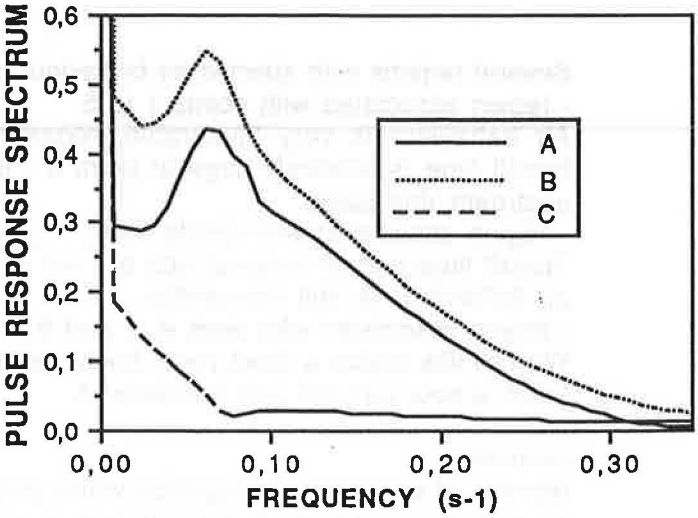
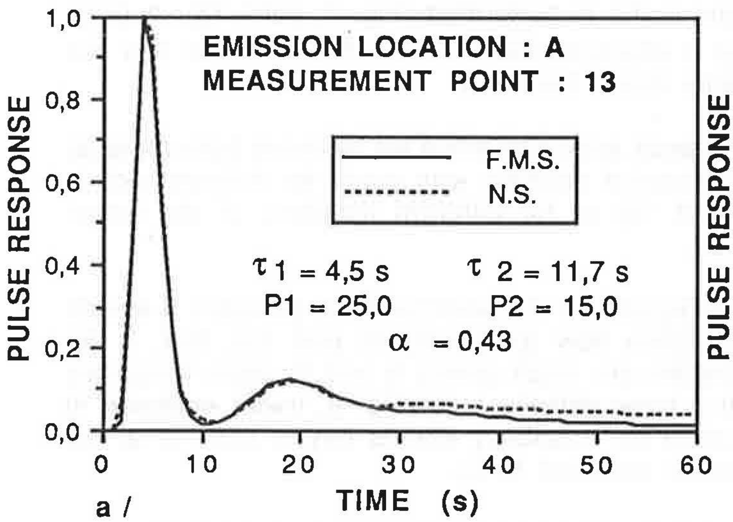
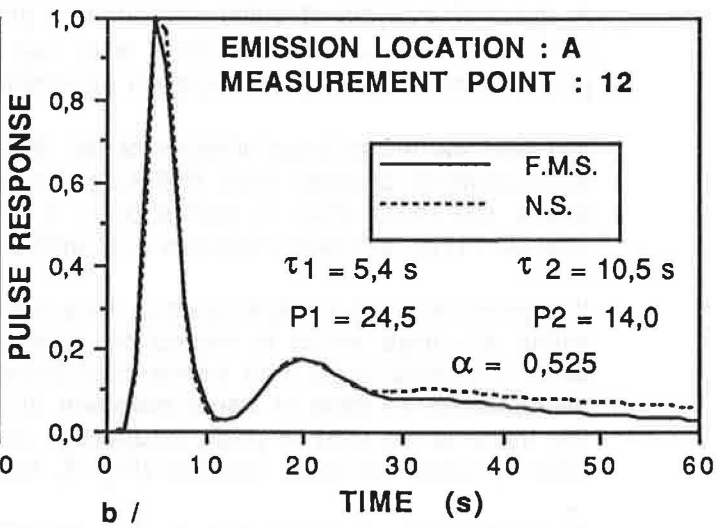


Fig. 8. Spectral analysis of the pulse response (tracer emission in different locations)





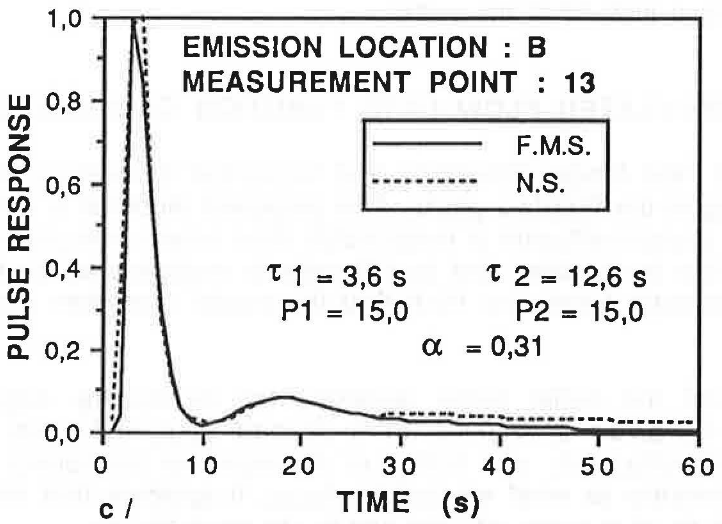


Fig. 9. Adjustment between Flow Model Simulation and Numerical Simulation

It is very comforting to note that the characteristic recirculation time given by the model (that is to say $\tau_1 + \tau_2$) is always very closed to the value we got by means of spectral analysis (16.1 s).

Two major reasons are responsible for discrepancies between curves (Fig. 9-a,b,c) when time is large enough :

1°/ As we said previously, diffusion from or to dead zones is not taken into account ; its influence arises for large times.

2°/ Until now, we only dealt with recirculated flow. But it should be more correct to deal with recirculated flow which contains tracer, because only one peak would be observed if no tracer was carried along by recirculation flow. Concentration distribution inside the room changes between two recirculation loops and we cannot honestly assert that the fraction of recirculated flow rate which contains tracer is time independent. It would be more appropriate to consider a fraction α given by $\alpha = \alpha(n)$ where n is the loop number.

4. CONCLUSION

The purpose of this paper was to put forward some parameters which can be used to optimize a general ventilation. Thus, ventilation has been characterized both on a local and on a global point of view.

We first proposed to split the pulse response in two parts, so that transit time and air renewal rate (or pollutant extraction rate) are calculated. In this way, behaviour of different fluids is more precisely analysed than in the context of internal age concept.

Then recirculation of fluid inside a room was characterized with two parameters : one represents recirculation frequency and the other expresses the fraction of recirculated mixing flow rate. To obtain this parameter, we used a systemic approach, similar to the one developped in chemical engineering, which allows, by means of basic flows, to get a physical model of a complex flow. It seems possible to use this approach in the case of simulations in real sites and to deduce the general structure of the flow inside a room.

For all the characterizations we considered in this paper, we will have to check that they give reliable results if we work in real sites.

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