ASSESSMENT OF THE SYSTEMIC APPROACH USING RADIOACTIVE TRACERS AND CFD

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ABSTRACT

An application of the systemic approach is presented for the study of the ventilation of a room in an industrial facility. First, a series of tracer gas experiments was made with a radioactive tracer. Analysis of the Residence Time Distribution (RTD) curves, supported by some CFD, then enabled to build a simple zonal model for the description and quantification of the observed air flow patterns. This model was able to reproduce the experimental RTDs inside the room as well as at the exhaust.

KEYWORDS

Air flow pattern, CFD, Residence Time Distribution theory, Tracer gas

INTRODUCTION

In order to help prevent hazards in industrial premises, the qualification of a proper air distribution system is essential. Such a qualification requires not only the measurement of the air change rate, but also a sufficiently detailed description of the air flow pattern. To achieve these goals, several tools are available, among which:

- gaseous tracers; when properly carried out and interpreted, a tracer-pulse experiment can yield detailed information on the circulation of air inside the room; a particularly interesting category of tracers are radioisotopes (Blet et al. 1997);

- Residence Time Distribution (RTD) analysis and systemic, or zonal, models; this approach was first developed for chemical engineering (Danckwerts 1953) but it seems to gain popularity in the ventilation community (Dessagne et al. 1994, Olander et al. 1995, Laborde et al. 1997). Zonal models are simple and cost-effective, but they should be handled with some care;

- Computational Fluid Dynamics (CFD); though CFD has received a lot of attention in the past years, numerical predictions of flows in complex 3D enclosures are not yet quite reliable (Nielsen 1994). CFD is nevertheless valuable to identify the main features of the flow pattern.

The aim of this paper is to emphasise the potential of the systemic approach, in so far as it is supported by sufficiently detailed tracer gas measurements. Confidence in the physical relevance of the systemic model can be enhanced by CFD calculations. The paper presents an application of this approach to the study of the ventilation of a room in an industrial facility.

EXPERIMENTAL

The room under study is not very large (5 x 4.5 x 3.2 m, i.e. 72 m^3 including internals) and separated in two unequal parts by a wall (Figure 1). It is ventilated by means of an air inlet and an exhaust duct. Air flow rate is 670 m^3/h, which corresponds to a nominal air change rate of 9.3 $hour^{-1}$.

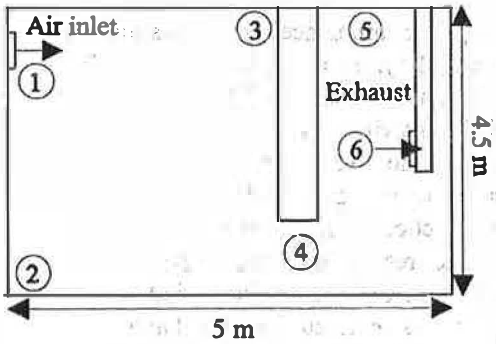

Figure 1 . Room layout

The tracer gas we used was ^{133}Xe, obtained by irradiation of natural xenon in a nuclear reactor. This gas is a gamma emitter (half life: 5.27 days, main gamma energy: 81 keV). Tracer activity was limited to 1850 MBq for each test, which allowed good measurement accuracy and limited exposure to radiation.

The gamma detectors are scintillation probes, composed of a NaI(Tl) scintillator, a photomultiplier and a voltage divider. They are calibrated prior to the experiment. Their response decreases very sharply with distance. Table 1 shows the relative intensity of the signal (i.e. signal at distance d over signal at distance zero) due to a ^{133}Xe point source, as a function of distance:

Table 1 Relative variation of signal intensity with distance.

Distance to detector (cm)	Relative signal intensity (%)
0	100
20	0.5
40	0.1
100	0.02

The signal from a detector can therefore be seen as a measurement of the volume-averaged activity in a sphere about 40 cm in diameter.

The tracer was injected as a pulse into the bulk of the air inlet flow. This provided a Dirac function as the input signal and also ensured good mixing of the tracer. Detection was performed at 6 points in the room (1 to 6 in Figure 1), including the inlet (point 1) and the exhaust opening (point 6).

The signals of the respective probes were continuously and simultaneously monitored (as counts per second) by a microcomputer with an acquisition frequency ranging from 0.2 to 100 Hz. This acquisition system can accommodate as many as twelve probes. The raw signal was corrected for radioactive decay of the tracer. After subtracting the baseline, the signal was smoothed and area-normalised. This procedure, performed by the Peakfit software package (Jandel 1995), lead to the local RTDs of the tracer in the room (Villermaux 1982).

This test was part of a series of experiments in a large industrial facility. Reproducibility was checked in another room, very similar in size and arrangement to this one. It was found to be quite satisfactory. Figure 2 shows typical RTDs (detectors 3 and 6). The signals from detectors 2 to 4 exhibit 2-3 peaks, which suggests there is a certain amount of recirculation inside the room. After about 100 s, the RTDs all decrease in a quasi exponential fashion.

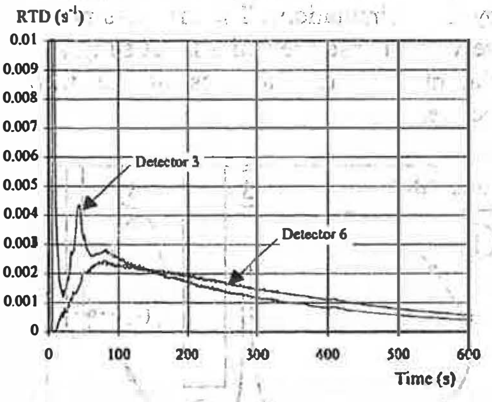

Figure 2 Experimental Residence Time Distribution curves

In our opinion, this experiment is a good illustration of the advantages of radioactive tracers. The time scale of the first peaks is very short (about 1 s), and it was nevertheless possible to monitor them at several locations simultaneously. To our knowledge, no chemical tracer system offers both of these features (unless several analysers are used - not a very economical solution when six points or more are required !).

RTD ANALYSIS AND CFD MODELLING

The RTDs show that the air flow successively reaches points 3, 4, 2, 6 (exhaust) and 5. Examining the layout of the room, it is possible to infer that:

- the blow opening creates an air jet, which flows across the room and impacts the opposite wall;
- it is then redirected as, more or less, a radial wall jet that reaches point 3 very quickly;
- this wall jet later reaches the space between the two parts of the room (point 4);
- at the same time, it creates a recirculation loop in the first part of the room. Point 2 is included in this loop;
- it then flows into the other part of the room and reaches the exhaust.

This (speculative) flow pattern is shown in Figure 3. We have tried to support it by CFD simulations. The idea was not to have very precise predictions, but simply to highlight the main features of the flow structure.

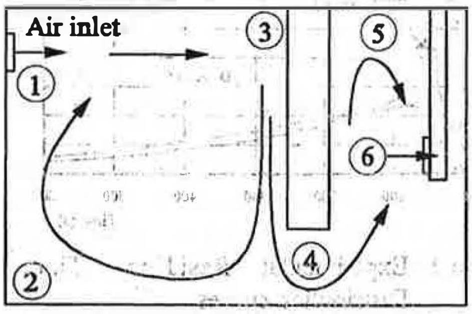

Figure 3 Postulated flow pattern

Simulations were made with the finite volume code TRIO-VF version 8.7 (Villand 1996), with a very coarse cubic grid (0.2 m in size). The turbulence model was the classical high Reynolds k-ε. First, the flow field was computed, then the RTDs were calculated by solving the convection-diffusion equation. The resulting concentrations were averaged over 8 mesh cells, to account for the « detection volume » of our probes.

The results did not compare badly with the measurements: the period between the peaks was correctly predicted and so was the exponential « tail » of the RTDs. On the other hand, the height and the number of peaks were grossly overestimated (Figure 4 shows a typical result: detector 3). Such a behaviour is quite typical in simulations of RTDs in ventilated rooms with TRIO-VF (Espi et al. 1998). It looks as though diffusion is underestimated in the calculations - a paradoxical finding in finite-volume computations with coarse grids ! Alternatively, the k-ε model may be inadequate.

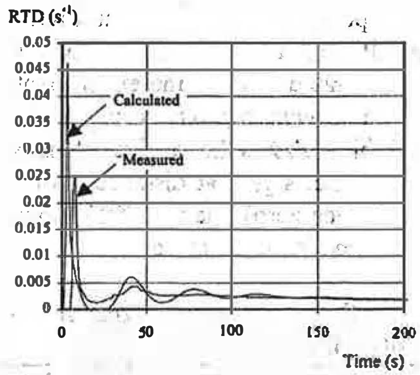

Figure 4 Experimental and calculated (CFD) Residence Time Distribution curves for detector 3

Almost miraculous agreement was achieved for detectors 5 and 6 (Figure 5 shows the results for detector 6, i.e. the exhaust opening); chance may however have something to do in that .... At any rate, we consider that our CFD simulation is « reasonably » successful and we are confident that it reproduces, at least in a qualitative way, the main features of the flow pattern.

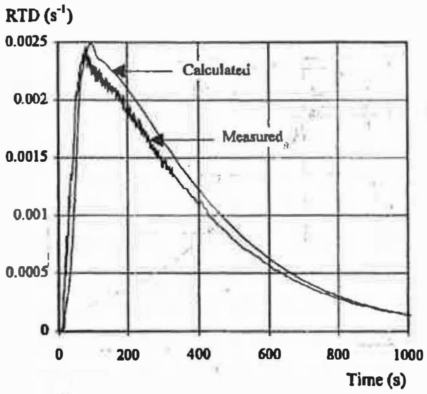

Figure 5 Experimental and calculated (CFD) Residence Time Distribution curves for detector 6

Figures 6a and b illustrate the transport of a tracer puff emitted in the air inlet, as calculated by the code, respectively 5 and 50 seconds after injecting the tracer; we are therefore using the simulation as a rather sophisticated smoke visualisation test - the advantage being that the entire concentration field is known as a function of time. The structures of the calculated flow are comfortingly consistent with the flow pattern that was inferred from the shape of t he RTDs (cf Figure 3).

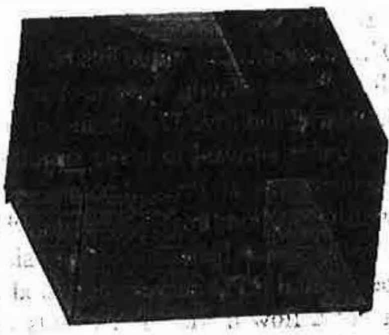

Figure 6a Concentration field in the room 5 s after tracer injection (the internal wall is in black)

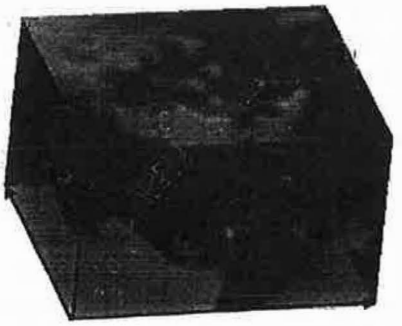

Figure 6b Concentration field in the room 50 s after tracer injection

ZONAL MODELLING

The circulation pattern in Figure 3 was then translated into a zonal model composed of plug flow elements and perfectly stirred tanks. The response of this model was calculated by means of the DTS software developed by PROGEPI (Leclerc et al. 1995). A « trial and error » process then allowed to optimise its structure, while trying to keep it as simple as possible. Model parameters were then determined by a built-in optimisation procedure. Our (fairly ambitious) aim was to have the best possible fit between calculated and experimental RTDs at all the measurement points - not at the outlet only. To our knowledge, this approach, based on a detailed set of experimental results, is a significant advance from the classical « inlet-outlet » analysis and, when successful, should greatly enhance confidence in zonal modelling.

Figure 7 shows the final flow model, where the recirculation loop is clearly identified; the location of the detectors is also indicated. This model is still quite close to the circulation pattern described above and we believe it retains physical significance.

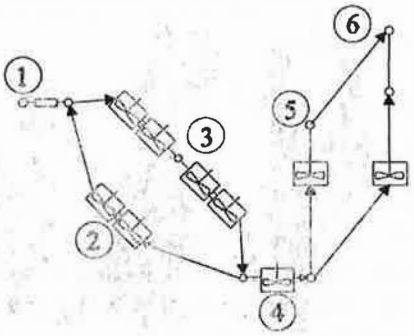

Figure 7 Structure of the zonal model

Agreement with experimental RTDs ranged from fair (detectors 3 and 4) to excellent (detectors 5 and 6), which is a proof of the relevance of our zonal model. We must however mention that the calculated RTD for detector 2 was too noisy to be exploited (this is a known problem with DTS; the response at nodes « near the injection point » may be incorrect). Figures 8 and 9 illustrate this comparison for detectors 3 and 6 (comparison with Figures 4 and 5 indicates that the zonal model is, not surprisingly, more successful than the CFD calculation).

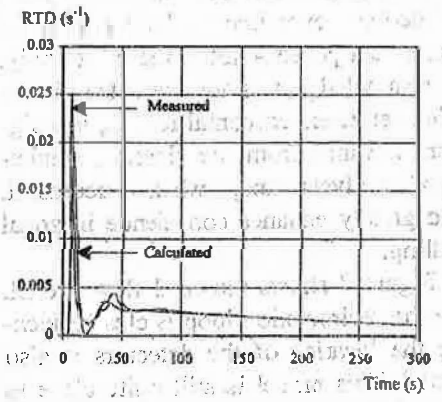

Figure 8 Experimental and calculated (DTS) Residence Time Distribution curves for detector 3

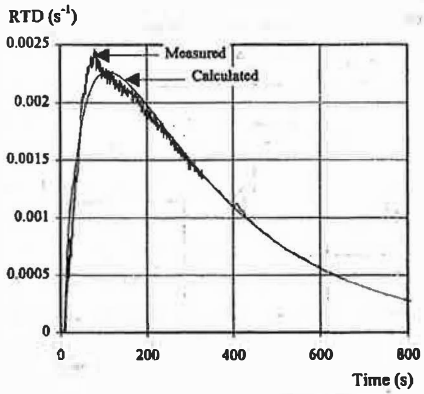

Figure 9 Experimental and calculated (DTS) Residence Time Distribution curves for detector 6

Model parameters give an estimate of flow rates and volumes in the different branches:

- recirculation is very strong (the flow in branch 2 is about nine times larger than the inlet flow rate); the volume of branch 2 is estimated at about 38 m^3;

- by comparison, the volume of « direct branch » 3 is only about 15 m^3;

- the cumulated volume of branches 4-5-6 is around 13 m^3; this is quite consistent with the dimensions of the part of the room beyond the internal wall.

CONCLUSIONS

The tracer gas technique has been used to qualify the ventilation system of a room in an industrial facility. The choice of a radioactive tracer allowed to make simultaneous measurements at several points in the room with very good time resolution, which proved to be quite beneficial. Analysis of the experimental RTD curves suggested the structure of a flow model. The results of a (rather crude) CFD calculation were consistent with that structure, which was then translated into an arrangement of plug flow elements and stirred tanks. With some parameter identification, this zonal model of the room reproduced quite satisfactorily the experimental RTDs, both at the exhaust and inside the room. This illustrates that it is possible to build a simple but reliable systemic model of the ventilation system.

On the other hand, we benefited from several factors: but for the presence of an internal wall, room geometry was not very complicated, the ventilation system was quite rudimentary, only one air flow rate was investigated ... and luck may have played some part in the success of our CFD simulation. This approach should therefore be tested in more complex situations (internal obstacles, multiple inlets or exhausts, diffusers...); a crucial test would also be the ability of the zonal model to emulate the RTDs with different ventilation flow rates, while keeping its original structure.

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