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STUDYING THE VENTILATION PATTERN IN A LARGE HALL BY THE COMBINED USE OF TRACER-GAS EXPERIMENTS, VELOCITY MEASUREMENTS AND NUMERICAL PREDICTIONS

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SUMMARY

At the nuclear reprocessing plant of La Hague (France), spent fuel elements are left to cool in storage pools before reprocessing. These pools are housed in large buildings (typical dimensions 95 x 25 x 6,5 m), ventilated by twelve ceiling diffusers and sixty-two exhaust slots located near the surface of the pool.

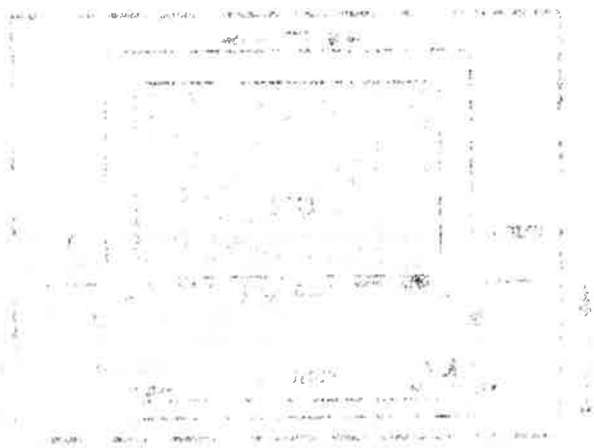
The operators of this facility raised several questions concerning this ventilation system :

- what are the movements of air in the building ?

- what are the transit times and transfer coefficients between the surface of a pool and the air sampling system?

- pool water temperature is normally kept at about 30 °C. In case of perturbation of the cooling system, this temperature would rise to an estimated 40 °C. How would the airflow in the building be affected ?

This paper shows how these questions could be addressed by the combined use of smoke injections, velocity measurements, tracer-gas experiments and the numerical predictions of a flow code.



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INTRODUCTION

This paper presents a part of the results of a study carried out on the ventilation system of the fuel storage pools at the nuclear reprocessing plant of La Hague (France). These pools are used to cool spent fuel elements before reprocessing.

Our paper focuses on one particular pool, which is housed in a large building (length 95 m x width 25 m). This building is divided up into several separate levels (figure 1); workers are normally present on the upper level only (i.e. the one above pool surface) so that only this level will be considered here. Although the building is much taller, this level is relatively low-ceilinged (height 6,5 m).

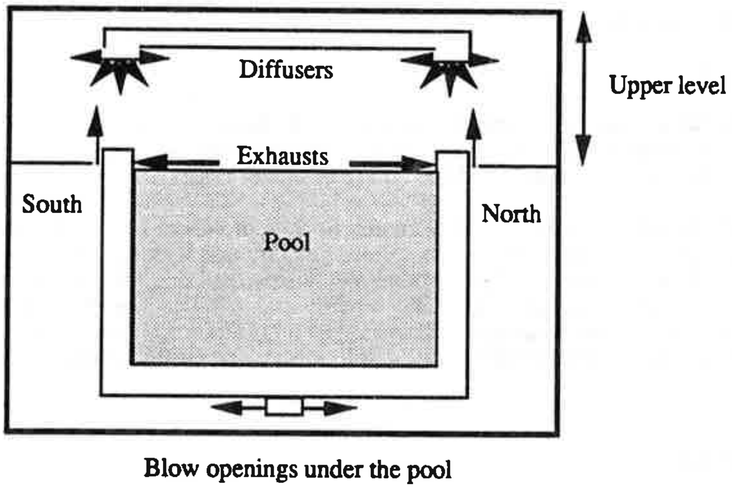

Fig.1. Cross section of the pool building.

Air is fed into the building by means of twelve ceiling diffusers and thirteen blow openings located under the pool; it is exhausted by sixty-two slots located near the surface of the water (figure 1). The air blown under the pool can reach the upper level through a grid located on each side of the pool. Exhaust flow rate (theoretical value 144,000 $m^3.h^{-1}$) is kept larger than blow flow rate (theoretical value 129,000 $m^3.h^{-1}$) so as to ensure a certain degree of dynamic containment.

The operators of this facility raised several questions concerning this ventilation system :

- what are the movements of air in the building?

- what are the transit times and transfer coefficients between the surface of the pool and the air sampling system?

- the fuel elements still give out a certain amount of thermal power. A cooling system keeps pool water temperature at 26 °C. In case of perturbation of this cooling system, this temperature would rise to about 40 °C. In what way would the airflow in the building be affected?

This paper shows how these different questions could be addressed by field measurements and theoretical calculations.

AIR MOVEMENTS IN THE BUILDING

Three approaches could be considered to answer the question of the movements of air in the building :

- numerical simulations,

- small-scale experiments,

- in-situ measurements.

It was not possible to make a numerical simulation of the flow of air in the whole building, considering its size and the complexity of the problem. Small-scale experiments had to be excluded for cost reasons, so we had to turn to in situ mesurements.

The experimental means that can be used in an industrial environment like our pool building are rather unsophisticated : smoke emissions, velocity and temperature measurements with simple probes and tracer-gas simulations. We used all of these, with the idea that the smoke injections could give coarse but directly usable indications, that could be refined by the use of the other techniques; the tracer-gas simulations came last because the information they provide is very rich but difficult to interpret in terms of movements of air.

Smoke injections

They were performed at different points in the vicinity of each diffuser. They showed the existence of clearly defined upward and downward currents at the same locations around each diffuser, as shown on figure 2.

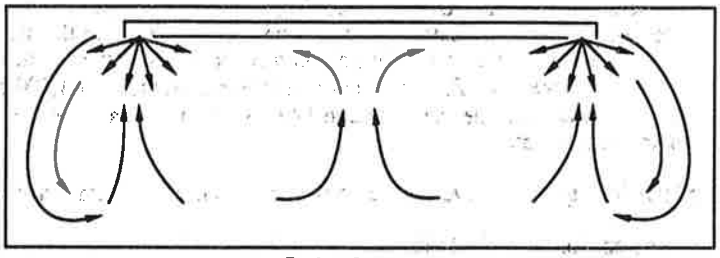

Fig. 2. Air flow pattern around the diffusers.

Velocity measurements

They were made at 1,5 and 5 m above floor level, along each side of the pool. No clear pattern was observed; this means in particular that the flux of air coming from the bottom part of the building does not create a jet-like structure as could be supposed from figure 1. Other measurements were also made at different points above the pool surface and in the rest of the building. They confirmed the existence of the "high" velocity (> 0,2 $m.s^{-1}$) and "low" velocity (< 0,05 $m.s^{-1}$) zones revealed by the smoke injections.

At this point of our study, we thus held the following view on the circulation of air in the upper level of the building : each diffuser creates its own ventilation "cell", these cells having approximately the same airflow pattern.

This finding is altogether not surprising (Vavasseur et al. also mention such a situation in [1]). The ventilation system comprises exhaust slots, blow openings under the pool, and ceiling diffusers. It is well known exhausts do not create a specific airflow pattern except for a very limited neighbourhood [2]. The velocity measurements showed that the air blown under the pool did not create any flow structure. The diffusers are thus the only device that can impose the airflow pattern, and this is made possible by the limited height of the enclosure (6,5 m). As a matter of fact, the same study was conducted in another pool building equipped with the same ventilation system, but of somewhat greater height (about 12 m). In that case, no clear airflow structure could be detected.

Temperature measurements

Air temperature was monitored continuously at five levels in the middle of the pool. The idea was to measure the vertical temperature gradient, which can be a useful indication on the vertical dispersion of pollutants.

We found there was indeed a warm air layer under the ceiling (temperature difference 1 to 2 °C), but this information could be not correlated in any convincing way to the observed movements of air in the enclosure.

Tracer gas experiments

We made several tracer gas experiments in the hope that they would confirm the "small-scale" periodic flow pattern shown by the previous experiments, and reveal larger scale movements superimposed on this pattern.

Sulphur hexafluoride (SF_6) was used. Measuring devices consisted of home-made chromatographs and continuous monitors. A complete description of the whole system can be found in [3].

Two series of tests were made :

a) Point injections

SF_6 was successively injected at two points in the middle of the pool (injection flow-rate 10 $cm^3.min^{-1}$); the injection points were respectively between and under the diffusers (figure 3). Concentration profiles were measured on each side of the pool, at heights 1,5 m and 5 m. A typical example of the resulting concentrations is shown on figure 4 (injection point 1, measurement on the northern side of the pool); it can be seen that the variation of the concentration is rather smooth and does not seem correlated to the position of the measurement point with respect to the neighbouring diffuser.

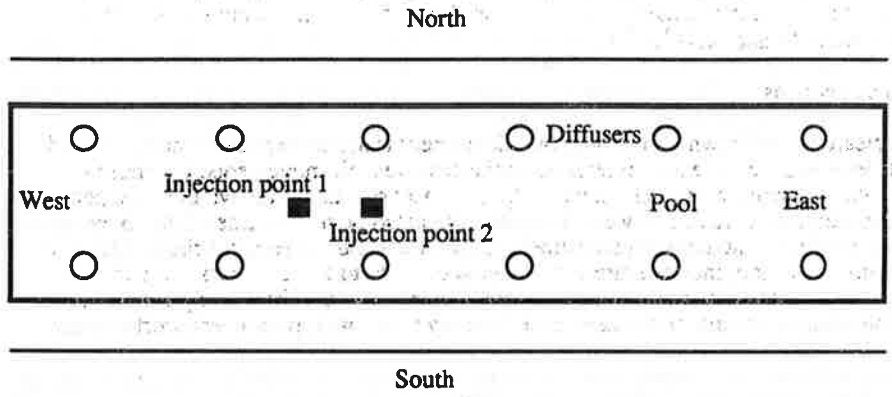

Fig. 3. Location of the injection points.

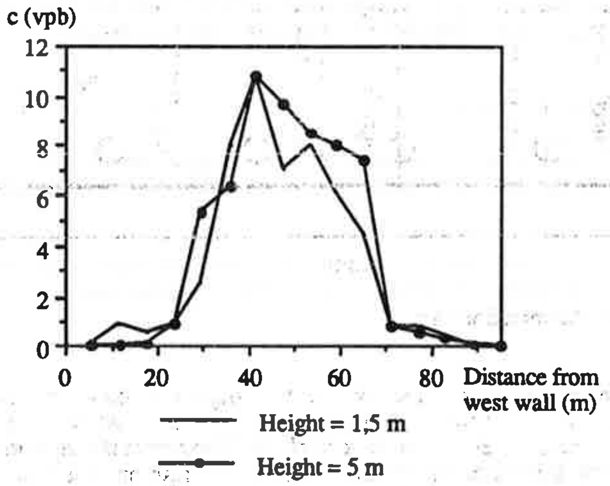

Fig. 4. Concentration profiles (injection point 1 - north side of the pool).

The following facts were observed :

- concentration profiles at 1,5 m and 5 m are quite similar;

- the overall shape of the concentration profiles does not change with the location the injection point;

- concentrations are clearly higher on the northern side of the pool; they are slightly higher in the eastern part. This indicates an overall movement of air to the north-east.

The results were then expressed in terms of transfer coefficient ζ, defined as follows :

$$\zeta = \frac{c}{q} \tag{1}$$

where c is the measured concentration and q the tracer-gas flow rate; ζ is theoretically independant of tracer-gas nature and injection flow-rate. The maximum values of ζ range between 2.10^{-2} and 8.10^{-2} $s.m^{-3}$.

b) line injections

The clearest fact shown by the previous experiment is the existence of a north-south dissymmetry. As we were also interested in the east-west air movements, we chose to perform another series of measurements with line injections across the width of the pool. As can be seen on figure 5, SF_6 was successively injected along five lines, 1 m above water surface; care was taken to locate some lines between and some under the diffusers. For each injection line, the measurement point was made to travel across the width of the pool, as far as possible along regularly spaced lines (it was unfortunately not possible to explore the whole surface of the pool, especially in the west part where works were under way).

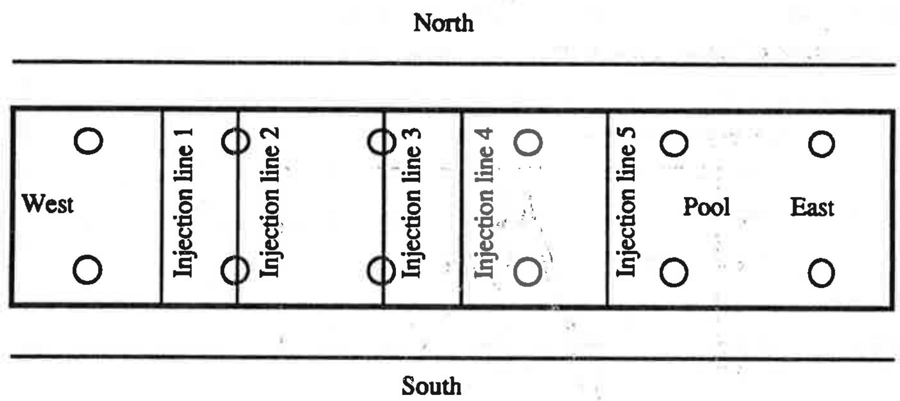

Fig. 5. Location of the injection lines.

The concentration profiles we obtained were clearly dependent on the distance to the injection line (figure 6). Near the injection (i.e. a few meters away), the profiles were highly non-uniform and presented one or several peaks. Far from the injection (more than 15 meters away), the concentration varied in a step-wise fashion. The latter observation fits well with the theory that each diffuser creates a "cell", in which the concentration should be uniform. We unfortunately found no evidence in support of that theory when we tried to reconstruct longitudinal concentration profiles - but since the measurement lines were rather sparse, this is not thought to be quite conclusive.

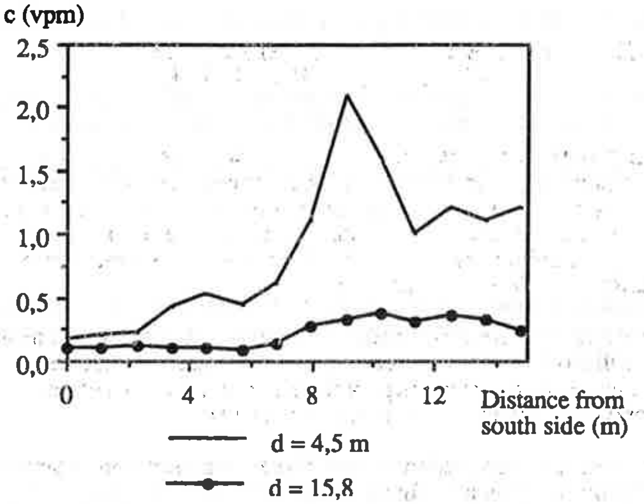

Fig. 6. Concentration profiles across the pool (injection line 3).
(d : distance of the profile to the injection line)

In almost all cases, the measurements exhibited an east/west or north/south dissymmetry. The following table compares the concentrations measured to the east and west of the injection line, and on each side (north and south) of the pool.

Injection line	East/west comparison	North/south comparison
1	*	N ≈ S
2	E > W	N > S
3	E > W	N > S
4	W > E	N ≈ S
5	W > E	S > N

* no measurement could be made west of the injection line

Table 1. East/west and north/south dissymmetry.

This indicates a preferential movement to the North-East in the western half of the pool (which confirms the results of the previous experiment) and to the South-West in the eastern half, the middle of the pool being very much like a plane of symmetry. This in turn can be interpreted by the presence of two large-scale recirculations. This interpretation remains of course hypothetical since there were no ceiling-level measurements to support it.

From a quantitative point of view, the values of the transfer coefficient defined by equation (1) range from 5.10^{-3} to 2.10^{-1} $s.m^{-3}$; they will not be given in detail here.

TRANSIT TIME AND TRANSFER COEFFICIENT TO THE SAMPLING SYSTEM

The air sampling system comprises four sampling points distributed in a regular way on each side of the pool. The transit times and transfer coefficients between the surface of the pool and the sampling points could be determined by simple tracer-gas experiments : a step signal of SF_6 was injected at some point at the surface of the pool; monitoring the concentration at a sampling point gave the transit time and a steady-state concentration from which transfer coefficient ζ could be calculated.

Seven such experiments were performed; six of them were devoted to a detailed study of the influence of the location of the injection point with respect to the ceiling diffusers on the transit time to the nearest sampling points. The results correlated rather well with the results of the previous section; they will not be given here.

In the last experiment, concentration was monitored at all sampling points; the injection point and the results are shown on figure 7.

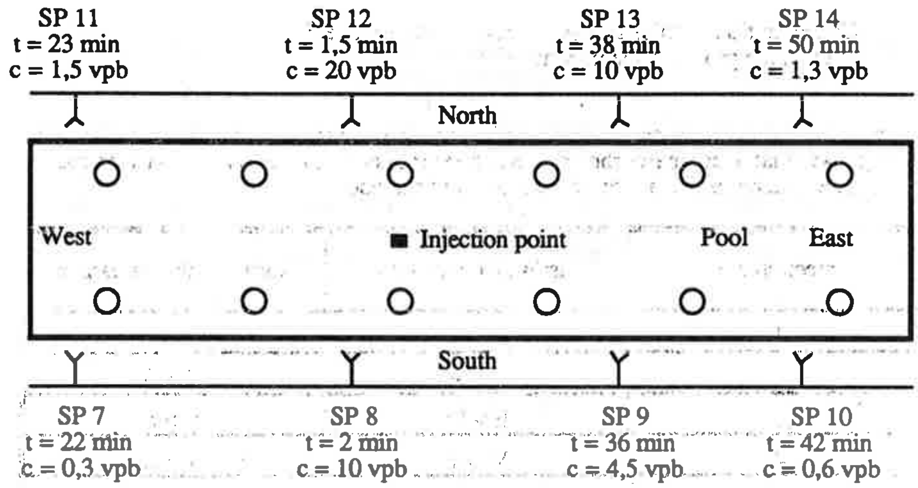

Fig. 7. Transit times and concentrations at the sampling points (SP).

The following facts can be observed :

- transit times to the nearest sampling points, 8 and 12, are short (about 2 minutes) but much longer to the other sampling points (22 to 50 minutes). This observation is in agreement with our theory of separate ventilation cells around each diffuser, exchanging matter through their common boundaries : sampling points 8 and 12 are in the same cell as the injection point, whereas the tracer-gas has to cross one cell to reach sampling points 7, 9 , 11 and 13 (transit times : 22, 36, 23 and 38 minutes) and two cells to reach sampling points 10 and 14 (transit times 42 and 50 minutes).

- transit times and transfer coefficients are obviously not correlated (see for example points 7 and 14), except in the neighbourhood of the injection point. One explanation may be that the tracer-gas may get more diluted in the swifter air currents.

- some degree of dissymmetry may be observed between the transit times on both sides of the pool; nevertheless, the differences are rather small (about 2 minutes except for sampling points 10 and 14) and are not thought to be significant. We find the same dissymmetry in transfer coefficients as in the previous experiment with injection line 3, which had the same location as the present injection point.

INFLUENCE OF WATER TEMPERATURE ON AIRFLOW PATTERN

For cost or feasability reasons, this question could not be treated by small-scale or in-situ experiments, so we had to turn to theoretical and numerical predictions.

A few theoretical considerations

The problem of the flow of air in the pool building is of course not amenable to analytical calculations but it bears some resemblance to two very classical models of natural convection :

- plane fluid layer : the pool building is assimilated to a flat box; temperature is imposed on the bottom (water surface) and on the top (ceiling) of this box;

- horizontal flat plate in infinite medium : the surface of water is assimilated to a flat plate where temperature is imposed.

The first model gives the best geometrical representation of reality. On the other hand, since the ventilation system indefinitely brings fresh air into the building, the second model is probably more realistic from the point of view of heat exchange.

In both cases, the intensity of natural convection is indicated by the Rayleigh number, defined by :

$$Ra = \frac{g\beta\Delta T L^3}{\nu\alpha} \qquad (2)$$

where g is gravity, β the dilatation coefficient for air, ν and α the kinematic viscosity and thermal diffusivity of air. ΔT is a temperature difference and L the length scale (height of the ceiling above the water surface for model 1, width of the pool for model 2).

The Rayleigh numbers for both models and for water temperature 26 and 40°C are computed in table 2.

Model	1		2	
Water temperature (°C)	26	40	26	40
Ra	$1{,}7.10^{11}$	$4{,}9.10^{11}$	$3{,}1.10^{12}$	$1{,}1.10^{13}$

Table 2. Values of the Rayleigh number.

These Rayleigh numbers are of course very high because of the large dimensions of our enclosure. This table shows that whatever model we use, the order of magnitude of the Rayleigh number does not change with water temperature, which is an indication that the effects of natural convection will be about the same.

Numerical predictions

The latter result was nevertheless not thought conclusive, so we used numerical predictions to get a better idea of the influence of water temperature. The TRIO flow code was used [4, 5].

Since the pool building is very large, it was not possible to represent it as a whole. The experiment fortunately showed that the movement of air could be divided into a small-scale flow pattern (around each diffuser) and large-scale movements. We chose to restrict our calculations to the small-scale movements (which anyway are the most important in terms of velocity) and thus to use a limited calculation domain containing only one diffuser; for symmetry reasons, this domain could even be reduced by half. Mesh grid was rather coarse (36 x 16 x 17, i.e.9792 nodes; average mesh size 0,4 m).

Three water temperature levels were used : 20 °C (water at ambient temperature), 26 °C and 40°C; feed air temperature was supposed to be always 20 °C. Because of the relative coarseness of the mesh grid, we could not use a fixed temperature condition at the air-water interface. We thus estimated the heat exchange between air and water by means of classical natural convection correlations and imposed the heat flux at the surface of the pool.

The results we obtained were velocity and temperature maps in fifteen cross-sections for each run, which cannot be analysed in detail here.

The velocity maps were difficult to interpret in terms of air circulation. The most remarkable features were an upward current under the diffuser and a downward current against the outer wall, which were indeed found experimentally; on the other hand, the code did not predict the upward current between the diffusers. As regards the influence of water temperature, the calculations showed that the flow pattern was not essentially altered when the temperature rose : only an acceleration by 0,1 - 0,2 $m.s^{-1}$ of the vertical currents was noticeable.

CONCLUSION

Our rather empirical approach thus enabled us to answer all the questions concerning the movements of air in a large pool building, by the use of fairly simple means. It is however clear that our experimental investigation was made much easier by the fact that there was some kind of periodic air flow pattern created by the blow openings, which allowed us to uncouple small-scale and large-scale movements. This means that our approach might have been at fault in other conditions, for example in an tall building. The fact remains that systematic tracer-gas experiments, with numerous injection points and measurement of concentration profiles over a large area, can give a wealth of information on the circulation of air in vast enclosures.

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