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PREDICTION OF GAS AND POLLUTANT DISTRIBUTIONS IN A VENTILATED CELL IN CASE OF FIRE

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ABSTRACT

Previous full scale experiments gave us a global and qualitative understanding of the gas circulation in a ventilated room in case of fire. In order to go thoroughly in the knowledge of these phenomena, we have built a scale model to perform more precise temperature measurements and more complete tracer gas experiments. The results show the existence of two zones when the air inlet is near the floor. At the opposite, when it is near the ceiling the room can be considered as a one single zone. Moreover, these experiments allow us to calculate the different exchange flow rates in the cell which are taken into account in the two-zones models. Finally, a few experimental conditions have been simulated with a two-zones fire model, Flamme-S, and comparisons with experimental results are presented.

keywords: air exchange efficiency, full and reduced scale experiments, tracer gas, modelling

INTRODUCTION

In case of fire in a ventilated room, contaminants and potentially toxic substances, handled in glove boxes for instance, can be released in the air and then spread through the exhaust opening in the environment. For safety reasons, it is therefore useful to understand and to forecast the circulation of gases in the cell.

FULL SCALE EXPERIMENTS

A first series of full scale experiments (Espi 97) were performed in a 100 m^3 room (figure 1). The room was ventilated thanks to a blow opening and an exhaust opening, both of which with two possible locations: near the floor or near the ceiling. The exhaust flow rate was set to 1000, 2000 or 2750 Nm^3/h (0°C and 1 atm) at the beginning of each experiment. The fire source was a burner located in the centre of the room and supplied with butylic alcohol. The heat release rate was kept constant during each experiment and equal to 45, 90 or 140 kW. All the configurations of ventilation (4 different positions and 3 flow rates) and the 3 heat release rates were tested: 36 experiments have been performed. Temperatures of gases were measured by a series of 27 thermocouples uniformly distributed on 3 horizontal levels: 50 cm above the floor, mid height and 50 cm below the ceiling.

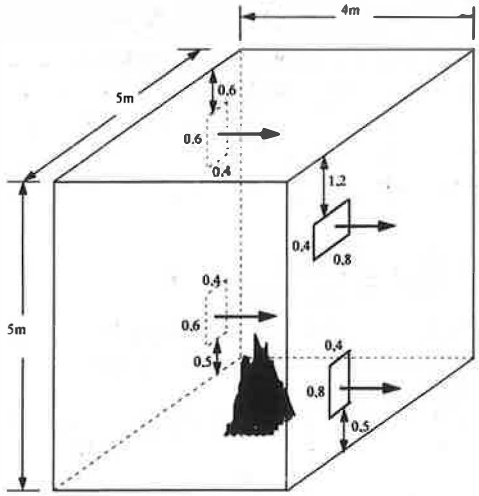

Figure 1 Full scale test facility

For all these experiments, the temperatures were found to be quite uniform on each horizontal level. Moreover, we could observe a very strong vertical stratification in case of air inlet near the floor. At the opposite, with the air inlet near the ceiling, the temperatures were much more uniform in the whole volume of the room. Unfortunately, as the vertical temperature resolution was coarse (1 thermocouple every 2 meters), we could not define exactly the location of the interface between the hot and the cold layers.

The most original part of these experiments was the release of a tracer gas puff (helium) in the flames. We monitored the evolution of the tracer gas concentration in the exhausted gases as a function of time thanks to a mass spectrometer. The plot of the logarithm of this concentration versus time showed first a peak and then a linear decrease. We could therefore define the air exchange rate (in hour^{-1}) as the inverse of the time constant of the exponential part of the concentration decay (Villermaux 85). We also defined a nominal air exchange rate as the total volume of the room divided by the exhaust flow rate. All the values are presented in table 1.

		1000 m^3/h	2000 m^3/h	2750 m^3/h
Nominal rate		11,0	22,0	30,3
BFEF	45 kW	6,8	10,0	25,0
	90 kW	8,2	13,0	19,5
	150 kW	7,5	13,7	17,4
BFEC	45 kW	13,8	24,9	36,0
	90 kW	14,2	29,7	44,8
	150 kW	15,1	24,3	45,3
BCEF	45 kW	11,5	17,9	29,1
	90 kW	10,5	20,3	29,1
	150 kW	10,7	21,0	30,0
BCEC	45 kW	13,2	18,7	30,8
	90 kW	11,8	21,3	29,5
	150 kW	13,2	20,2	32,5

Table 1 Full scale air exchange rates (h^{-1})

abbreviations: B: Blow opening
E: Exhaust opening
F: near the Floor
C: near the Ceiling

We remark that the experimental air exchange rates for BFEF are lower than the nominal ones. This can be explained by the position of the interface between the two layers: the combustion products released in the upper layer must leave the room by the exhaust opening, so the interface must be located below the top of the exhaust opening, as shown on figure 2; if such is the case, only a part of the total exhaust flow rate is used to extract hot gases from the upper layer, so that the resulting air exchange rate is lower than expected.

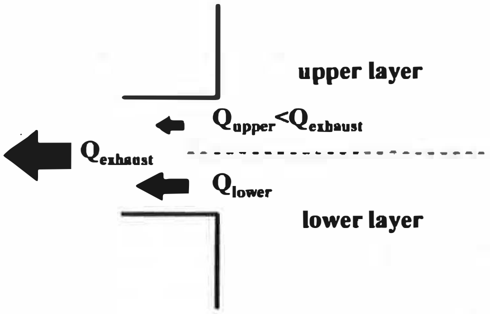

Figure 2 interface position when exhausting near the floor

At the opposite, the air exchange rates for BFEC configuration are higher than the nominal ones. Thanks to the temperature measurements, we know that the interface between the two zones must be located below mid height, so the entire exhaust flow rate has to go through the upper layer. Since the upper layer volume is clearly smaller than the total volume of the room, the air exchange rate should indeed be larger than the nominal one.

For BCEC and BCEF configurations, experimental air exchange rates are relatively close to the nominal ones, but it is much more difficult to explain the gas circulation because of the blow opening position: the fresh air enters the room in the hot layer, and because of the density difference between hot and cold gases, the entering jet tends to fall down. So we can suppose that this cold air jet crossing the hot layer improves gas mixing in the room.

In conclusion, with these full scale experiments we have obtained a global and qualitative understanding of the gas circulation in the cell. Nevertheless, spatial temperature resolution was poor and we had no information on tracer gas evolution inside the room. These are the reasons why we have decided to obtain more quantitative data by performing more thorough new experiments. Full scale experiments have the drawback to be difficult and time-consuming, so we decided to perform these experiments in a reduced scale cell. Moreover, we wanted to obtain local velocities using the PIV (Particle Image Velocimetry) technique and this was only possible with transparent walls, not with the concrete walls of the full scale facility.

REDUCED SCALE EXPERIMENTS

The design of the scale model has been realised in following the mathematical considerations of Quintiere et al (77) and Thomas (63). We have chosen 10 mm thick walls in hardened glass because of its transparency and its thermal and mechanic resistance. We have also imposed a geometrical factor of similarity of 1/5 for practical reasons. Out of the 10 dimensionless numbers presented in the study of Quintiere, derived from the conservation equations governing the gas and solid phases, two have been kept constant:

$$\Pi_1 = \frac{gL_r}{V_r^2} \qquad (1)$$

$$\Pi_2 = \frac{\sqrt{L_r}\dot{q}}{\rho_r C_p T_r \sqrt{g}} \qquad (2)$$

with
- L_r = reference length
- g = gravitational acceleration
- V_r = reference velocity
- T_r = reference temperature
- C_p = specific heat of air
- ρ_r = reference density
- $\dot{q}$ = volumetric heat release rate

The other dimensionless numbers could not be kept constant because of our choice for wall material. But, according to Quintiere, Π_1 and Π_2 are the most important numbers to achieve similarity. The frame of this scale model is made of stainless steel as well as the floor. The burner we used is a cooker burner supplied with butane and located in the centre of the cell. The heat release rate is in similarity with the full scale experiments that is to say constant during each experiment and equal to 0,8 1,6 and 2,5 kW. The exhaust flow rate is ensured by an air jet pump. The blow opening is kept free. We have performed the experiments in similarity with the full scale, except those with the exhaust flow rate at 2750 m^3/h because it could not be achieved with the scale model facility. The reduced scale air exchange rates are compared to the full scale ones on figure 3. We can observe a very good agreement between full and reduced scales experiments. This indicates that similarity between the two scales is correct.

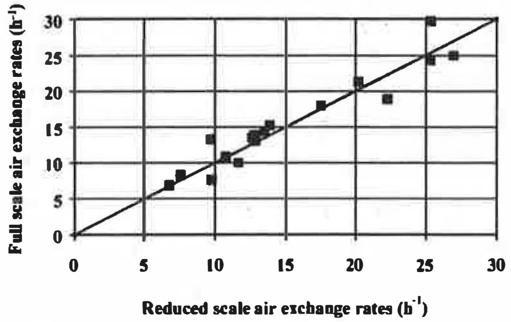

Figure 3 Comparisons between the two scales

In the scale model, we have also released puffs of tracer gas in both upper and lower zones and then monitored the helium concentration simultaneously in the 2 layers, inside the cell. The results show that when the air inlet is near the ceiling, the concentrations anywhere in the cell are relatively close together (figure 4). At the opposite, when the air inlet is near the floor (figure 5), the concentrations are very different. This phenomenon shows that we have two well defined layers when the air inlet is near the floor and that we can not split the volume of the cell in 2 zones when air inlet is near the ceiling. This is in perfect agreement with the observation we made with the full scale experiments.

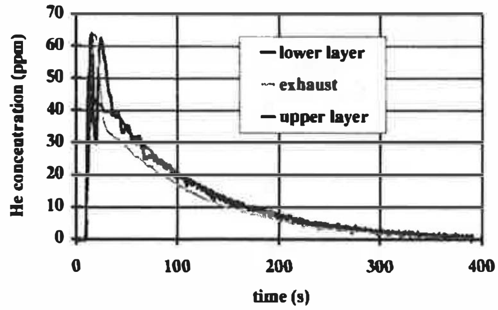

Figure 4 Evolution of the He concentration in the cell when blowing near the ceiling

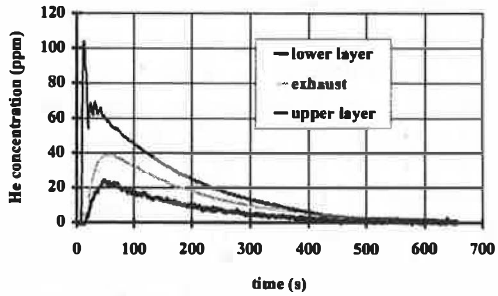

Figure 5 Evolution of the He concentration in the cell when blowing near the floor

It has to be mentioned that for the same experimental configuration, the air exchange rate deduced from the final exponential decay is independent from the locations where the puff is released and where the helium concentration is monitored. So the air exchange rates we have found are applicable to the exhausted gases, but also anywhere in the cell, whatever the scale is.

Now that the validity of the 2 zones model has been demonstrated when the air inlet is near the floor, it is possible to quantify the different flow rates taken into account in this model (figure 6).

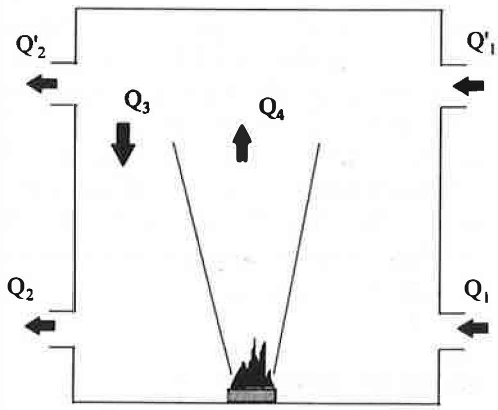

Figure 6 Flow rates taken into account in the two zones model

To this end, we have used the tracer gas technique with continuous release in the lower or in the upper layer (S_l and S_h) and looked at the steady-state helium concentrations in both zones (C_l and C_h). For one experimental configuration, 2 tracer experiments have to be performed: the first one (superscript 1) with He release only in the lower zone, and the second one (superscript 2) with He release in the upper zone. All the equations resulting from simple He mass balances are presented below:

$$Q_2 = Q_e \frac{C_e - C_h^1}{C_l^1 - C_h^1} \quad (3)$$

$$Q'_2 = Q_e \frac{C_e - C_l^1}{C_l^1 - C_h^1} \quad (4)$$

$$Q_3 = \frac{S_l^1 C_l^2}{C_h^2 C_l^1 - C_h^1 C_l^2} \quad (5)$$

$$Q_4 = \frac{S_h^2 C_h^1}{C_h^2 C_l^1 - C_h^1 C_l^2} \quad (6)$$

$$Q'_1 = Q'_2 + Q_3 - Q_4 \quad (7)$$

$$Q_1 = Q_2 - Q_3 + Q_4 \quad (8)$$

where subscript e corresponds to the exhaust.

All the flow rates are in Nm^3/h.

The experimental results are summarised in table 2:

confi gu ration	heat release rate	Q_e	Q_1/Q_e	Q_2/Q_e	Q_3/Q_4
BFEF	0,8 kW	20,0	86%	68%	0,64
	1,6 kW	19,2	88%	58%	0,50
	2,5 kW	18,4	81%	34%	0,37
	0,8 kW	40,6	93%	90%	0,96
	1,6 kW	39,5	81%	89%	1,17
	2,5 kW	38,0	91%	80%	0,79
BFEC	0,8 kW	18,3	89%	0%	0,21
	1,6 kW	17,2	88%	0%	0,16
	2,5 kW	15,5	79%	0%	0,18
	0,8 kW	38,4	66%	0%	0,22
	1,6 kW	34,5	75%	0%	0,23
	2,5 kW	32,3	67%	0%	0,24

Table 2 Experimental flow rates in the scale model

It has to be mentioned that Q'_1 and Q'1 can be deduced from table 2 thanks to equation (9).

$$Q_1 + Q'_1 = Q_2 + Q'_2 = Q_e \quad (9)$$

For the BFEC configuration Q'_2/Q_e is set equal to 100% because the interface is located below the exhaust opening, so that the entire exhaust flow rate comes from the upper layer. We can remark that, as the air inlet is near the floor, a part of the flow rate seems to go directly to the upper layer (Q'_1). This can be explained by the fact that the incoming air jet crosses the room, impacts the opposite wall and spreads radially. So a part of the jet goes up along the wall and, if the velocity is large enough, a part of this flow rate can cross the interface and reach the upper layer.

THE 2 ZONES MODEL APPROACH

The logical next step is to test these experimental results with numerical simulations performed with a 2 zones code. The code we used is Flamme-S (Malamas 95), which has been developed at the French Nuclear Agency (Commissariat à l'Energie Atomique: CEA). For each configuration we have simulated, different parameters were imposed with the experimental data: the heat release rate, Q_e, Q_1/Q_e, Q'_1/Q_e and Q_3/Q_4. Then we have simulated a puff release in the flames and calculated the air exchange rate at the exhaust. The fact that we take the experimental data to run the code does not make the simulations useless: first, the flow rate from the plume is not imposed, but calculated by the code according to the Gupta model. Moreover, the experimental data come from a continuous release experiment which gives much less information than a puff release. So using a part of these experimental data does not necessarily lead to good results in simulating helium puffs.

Four simulations have been performed and the comparisons with experiments are presented table 3.

configuration	experiment	simulation
BFEF 23 m^3/h 0,8 kW	6,8	6,0
BFEF 46 m^3/h 2,5 kW	12,8	13,8
BFEC 23 m^3/h 0,8 kW	12,7	12,6
BFEC 46 m^3/h 2,5 kW	25,3	21,2

Table 3 Comparison between experimental and numerical air exchange rates (h^{-1})

These results are in correct agreement within 20 %, but we have to make a thorough comparison between experiments and simulations: the air exchange rate is only one of the different parameters which can be used to compare the results. For example if we look at the interface height, we observe that it is higher in the simulations than in the experiments. Although the simulated air exchange rates are quite correct, there is perhaps an important error in the calculation of the plume flow rate due to the fact that the Gupta model is only valid in unconfined conditions.

WORK IN PROGRESS

As mentioned before, we have to take a closer look in comparing experiments and numerical simulations performed with Flamme-S.

We are also currently testing a field modelling code, TRIO-VF, also elaborated at the CEA. To make fine comparisons, we are using the PIV technique to obtain local velocities fields in two dimensions.

CONCLUSION

We have seen that the similarity approach gives good results. The experimental data obtained can therefore be transferred to the full scale room. The results show the existence of two layers (an upper hot one and a lower cold one) when the air inlet is near the floor, and that the room can be considered as a single zone when blowing near the ceiling. The two zones code Flamme-S has been tested for these experimental configurations and seems to give good results, but thorough comparisons have to be achieved before concluding

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