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MODELLING A PAINTING AREA BY RESIDENCE TIME DISTRIBUTION (RTD)

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SUMMARY

The following paper presents the Residence Time Distribution (RTD) type modelling of the ventilation system of a painting area. This work has completed a more traditionally established assessment of the performance of the installation (mean age, air exchange efficiency).

Using "RTD" concepts, real flow can be modelled by means of a network of elementary volumes symbolising the basic functions (piston flow, perfect mixing). This type of representation provides a simulation of the concentration response in an air outlet for a tracer injection at the inlet. The system was identified by adjusting the parameters of a supposed model so that its pulse response coincided with that measured. Although this technique does not provide a unique representation of the flow, and to a large extent requires imagination on the part of the user, it can be employed to validate or exclude different ventilation system scenarios.

The painting area studied is divided into two zones. Each has a ground-level extraction system and a compensation air inlet system made up of low-velocity diffuser in conjunction with air jets delivered by nozzles.

INTRODUCTION

Residence Time Distribution (RTD) modelling was carried out to complete the performance assessment of a ventilation installation. This approach was adopted on account of the particular configuration of the premises studied - a painting area - which did not allow the standard criteria (air exchange efficiency, ...) (Sandberg and Sjorberg, 1983) to be applied with sufficient certainty. Indeed, as this type of workshop is not enclosed, its volume is not definite, and the air flows entering and leaving are poorly controlled.

RTD type modelling provides intermediary results between a map resulting from numerical simulation and reducing factors such as age or air exchange efficiency. The model obtained is midway between a geographical and a functional representation of the flow pattern. It can only be used to analyse an existing situation and is in no way suitable for predictive use ; it is simply the result of a particular usage of the concentration response curves. As from 1969(Chen et al., 1969), this approach was used to model the ventilation of a chamber fitted with one air inlet and outlet, and then quickly abandoned in favour of numerical simulations. In 1995, Olander (Olander, 1994, 1995a and 1995b) employed this type approach in the laboratory on a cabin fitted with a general ventilation system and local exhaust device.

This paper presents both the general principles of the « RTD » method and the approach that led to obtaining a validated model of the premises studied.

PRINCIPLE OF RDT MODELLING

The RTD concept, introduced by Danckwerts (Danckwerts, 1953) in 1953, is nowadays in widespread use in the chemical engineering sector (Villermaux, 1982). Used in conjunction with chemical kinetics, the global information on fluid circulation can provide a forecast of the performance of reactors.

In an RDT model, the flow is represented by means of interconnected elementary volumes (modules). These modules symbolise the basic flow patterns (piston flow, perfect mixing), the pulse responses of which can be easily recognised (see figure 1). In addition to the shape of the response, they are defined by the volume that they occupy and by the flow rate of the fluid passing through them.

Using an imaginary network and software (Leclerc et al., 1995), it is possible to simulate the concentration responses to a tracer injection. Adjusting the simulated curves to those measured allows the description adopted for the flow to be validated. With this approach; the solution is not unique, but for the model to be credible it must be constructed from a maximum of physical information stemming from the system being studied.

The development of a model therefore requires three successive stages :

1) Record the concentration response curves in the air outlets for material injections at the inlet. At this stage, and with a little experience, it is already possible to appreciate the nature of the flow.
2) Construct the network of modules representing the flow. The user incorporates, by means of the structure retained, the information collected by visualisation with a smoke generator or by prior knowledge of the physical laws governing certain flows (air jet, dead zone linked to the presence of an obstacle, etc.).
3) Adjust the parameters of the model. For each module, the volumes, the flow rates, and the parameters linked to the shape of the response are refined by iteration. The model will be globally valid if the retained parameters are physically meaningful, and particularly if they respond to the clear constraints linked to the material balance and volume balance.

DESCRIPTION OF THE VENTILATION INSTALLATION

The 67 m^2 painting area is located in a large workshop. It is divided into two areas by 5.85 metre high partitions (figure 2). Each is fitted with a floor extraction grille (3 m x 5 m) and a compensation air inlet system. The latter, at a height of 8.4 m, includes a plenum (1.4 m x 5 m) surrounded by two rows of 14 jet nozzles ($\varnothing$ 70 mm). The clearance between the partitions and the air compensation system allows the passage of a travelling crane.

The global supply flow rate was 27,000 $m^3.h^{-1}$ and that of the extraction system 35,000 $m^3.h^{-1}$. The two zones were never used simultaneously for spraying, one being used for drying while the operator painted in the other. To improve the decontamination of the working zone, air flow distribution is linked to the activity : $\approx$ 15 % for drying and $\approx$ 85 % for spraying. The reduction in the compensation air flow rate in the area selected for drying is obtained by shutting off the damper at the inlet to the plenum. The compensation air is heated in cold weather.

During the measurements, the overhead crane was outside the painting area, and this situation was favourable in terms of air exchange efficiency. The difference between the air inlet supply temperature and the ambient temperature was 8°C. Spraying took place in zone Z1 and, as a result, the damper for zone Z2 was closed.

MODELLING

The response curves

On account of both access and mixing distance, the different inlet systems were not measured individually. The helium tracer was therefore injected into the entire compensation air flow. The concentration responses were recorded by sampling in the extraction ducts of zones Z1 and Z2.

These two responses (figure 3), came from an eight second injection and were very similar. The presence of a peak with an almost vertical slope indicates that a proportion of the air quickly crossed the volume, the steady decrease being the result of a mixing-type function. This mixing can result either from mixing action or from fast re-circulating of part of the flow crossing the volume.

The network of modules

Developing a network of modules is a delicate task. It must take account of the flow whilst having a degree of complexity adapted to the situation : too simple and the response curves cannot be adjusted ; too complex and numerous variables have to be optimised, not to mention the increased difficulty in interpretation. With this in mind, the initial network was kept deliberately simple and able to be upgraded as required.

Before providing a network-type diagram, a more traditional flow representation is given (figure 4), and the elements employed to develop it are indicated below.

- The brief visualisation with the smoke generator highlighted flows of differing natures in each zone. In the lower part of Z1, the flow is relatively organised and only rises up slightly close to the wall. In the upper part, these upward movements are more pronounced. Part Z2 clearly shows areas of descending current along the entire height (under the influence of jets) and agitated areas of rising current.
- Although it was not possible to observe the flow between the top of the walls and the compensation system it is possible to put forward hypothesis. This zone, hereafter termed "air supply zone" was agitated by the jets. An induced flow was created in the first few decimetres after the inlets, where they could be considered as free jets.
- The concentration measured in the extraction duct, following a continuous tracer injection into the air compensation, allowed a global flow rate circulating in the volume studied to be determined. This flow rate was estimated at 45,000 $m^3.h^{-1}$. Subtracting the flow provided by the air compensation (27,000 $m^3.h^{-1}$) indicates an infiltration flow rate of 18,000 $m^3.h^{-1}$ (figure 5). The same calculation for the extracted flow (35,000 $m^3.h^{-1}$) gave an exfiltration rate of 10,000 $m^3.h^{-1}$ (figure 5). These uncontrolled air flows entered and left via the upper part of the booth.

The representation in figure 4 was not converted directly into a module network. Indeed, a RDT type representation is, above all, a functional flow model, and it is for this reason that simplifications can be introduced by grouping volumes fulfilling the same function. For example, in the case of zone Z2, all that is required is to retain a « piston-flow » function to represent the jets and a varying « mixing » function for the upward air movement.

To construct the network (figure 6), 11 volumes were retained.

Firstly, that representing the majority of the « air supply zone ». Identified by branch **XVII** (the reduced sized diagram included in figure 6 indicates the branches quoted in this paragraph), it is fed with air by the upward air movement of Z1 (**XVI**) and Z2 (**XVIII**) as well as by the air coming from the premises (XIX). It is in this volume that inlets take the induced air (branches XXII, XXIII, XXIV). The air sent back into the premises (XX) also transits this volume.

Branches **IV, XXI** et **XII** represent the supply air from the plenum chamber side Z1, the nozzle side Z1 and the nozzles side Z2 respectively; branches **V** , **X** and **XIII** are their extensions in the lower part. Branches **VI** et **XIV** designate the extraction of side Z1 and side Z2.

The absence of a direct link between the jets (XIII) and the upward air movement (XVIII) assumes that the exchange between the two currents is low.

Although figure 6 illustrates the «piston» and « mixing » type elements, all the modules are described by means of series mixers where the J number is adapted to the flow (see figure 1). The J number selected must definitely take into account the volume of the module ; figure 7 shows the advantages of using the J number / volume ratio. Proposal « a » represents a piston type flow (J = 48) and is equivalent to « b » on account of the definition of a series mixer. Proposition « c » still has the same flow but is composed of a module where J = 45 and a module where J = 3.

The parameters of the network

The network is made up of 24 branches of which 11 contain modules. On the basis of one variable per branch (a flow) and of two additional variables per module (the volume and the J value), the gross number of parameters is 46.

In reality, the number of unknowns is very much lower. On the one hand, the equality of the incoming and outgoing flows to each node already reduces the number of « flow » type unknowns to three. On the other hand, the physical volumes of the zones « air supply », « Z1 » and « Z2 » impose restrictions on the volume of the different modules.

Furthermore, the parameter variation ranges are limited. Indeed, the visualisations with the smoke generator allowed acceptable ranges to be imposed for certain volumes, branch XIII, for instance representing between 20 % and 40 % of zone Z2. In addition, at an equal volume, the J number associated with a module decreases in accordance with the distance from an inlet as the flow is less and less piston-like. It is also possible to take advantage of certain velocity measurements ; for instance, a velocity of 0.5 $m.s^{-1}$ measured in the zone symbolised by branch XIII then related to the distance to cross (around 6 m) provides an approximation of the flow/volume ratio. Finally, certain branches fulfil the similar functions for sides Z1 and Z2, and the parameters characterising them therefore must be of the same order By further adding that the flows and volumes are positive values, the room for manoeuvre in adjusting the parameters is greatly reduced.

All these restrictions, managed by means of a spreadsheet, led to around ten iterations for the solution proposed in Table 1 (curve adjustment is illustrated in figure 8). To achieve these simulations, modules

/ere added to take account of the transfer functions of the measuring equipment (measurement cell, ampling pipes, etc.).

NTERPRETATION OF RESULTS

:he poor operation of zone Z2 was confirmed by the model : two thirds of the supply air flow rose after :rossing the polluted zone. Indeed, as the initial flow of the jets increased by 220 % due to induction :ffect, the extraction (5,000 $m^3.h^{-1}$) was no longer able to evacuate the 16,000 $m^3.h^{-1}$ supplied. In zone Z1, ılthough the majority of the volume(87 %) was crossed by an air flow directed towards the extraction ;ystem, more than half of the flow rose in the upper section.

[n zone Z2, reducing in the air flow delivered by the jet nozzles would certainly improve the performance ɔf the installation.

DISCUSSION

The results put forward in this paper stem entirely from the network proposed in figure 6. The satisfactory correlation between the measured and simulated curves, obtained whilst taking into account the observed system, have allowed it to be validated.

A more complex network was also tested : it included an exchange between the supply air flows and the upward air movements (branches XIII↔XVIII and X↔XVI). Adjusting the curves led to imposing a negligible flow for this exchange and therefore to return to the initial network.

The sensitivity of a number of parameters was tested, in particular the flow induced by the jet nozzles. The curves were also able to be adjusted, whilst respecting the constraints, to values varying between 200 % and 300 % with an optimum of 220 % of the flow delivered by the nozzles.

CONCLUSION

In the study of this paint area, RTD type modelling has allowed both the establishment of a validated flow representation and quantification of the principle parameters describing the flow. This type of modelling is a useful addition to smoke generator type visualisation. It has provided an overall confirmation of what the visualisation often partially and locally demonstrated.

This method, most often used to model chemical reactors, has not been documented to any great extent as regards the parameters measured within the volume studied ; adjusting the parameters could be facilitated by correlating the J number, which characterises the agitation of a zone, to the physical factors such as air turbulence.

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Zone	branch	Name	Volume m^3	Volume % zone	Flow m^3.h^{-1}	J	J / volume m^{-3}
Z1	V	plenum	60	35	51,000	4	0.07
	X	jet	37	22	16,000	6	0.16
	XVI	upward movement	22	**13**	37,000	1	0.05
	VI	extraction	50	30	30,000	10	0.2
Z2	XIII	jet	52	35	**16,000**	7	0.14
	XVIII	upward movement	95	**64**	11,000	2	0.02
	XIV	extraction	2	1	**5,000**	4	2
Air supply	XVII	mixing	172	86	66,000	1	0.01
	IV	plenum	20	10	17,000	20	1
	XXI	jet side Z1	4	2	5,000	20	5
	XII	jet side Z2	4	2	5,000	20	5
	XXII	induced air (plenum)	-	-	34,000	-	-
	XXIII	induced air jet side Z1	-	-	11,000 (220% of jet side Z1)	-	-
	XXIV	induced air jet side Z2	-	-	11,000 (220% of jet side Z2)	-	-

Table 1 : parameters of the model. The «upward air movement» involve 13 % of the volume of zone Z1 versus to 64 % in zone Z2, furthermore, two thirds of the supply air flow in this zone rises

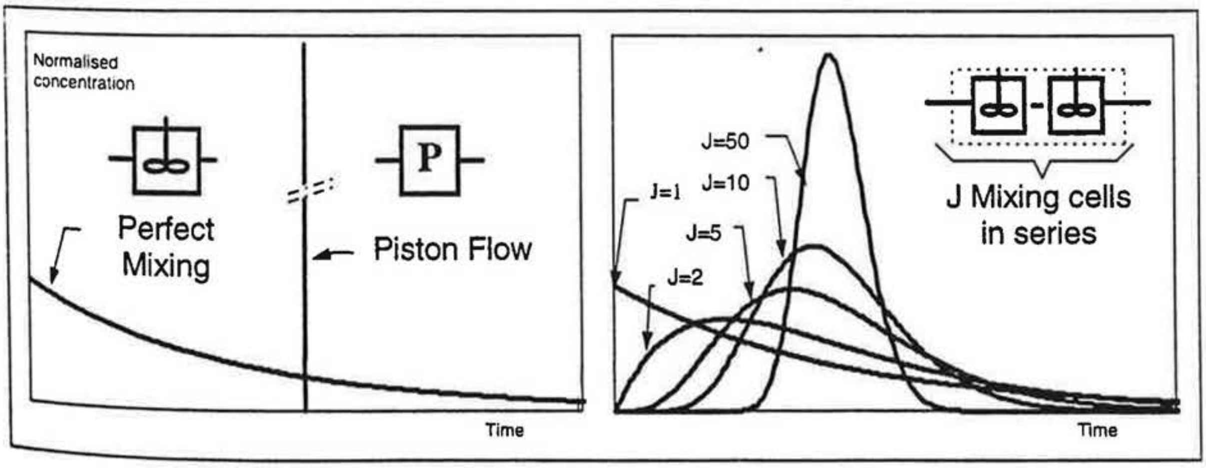

Figure 1 : response curves for the « basic » flows. The series mixing cells provides progressive passage from « perfect mixing » (J = 1) to plug type flow (J infinite)

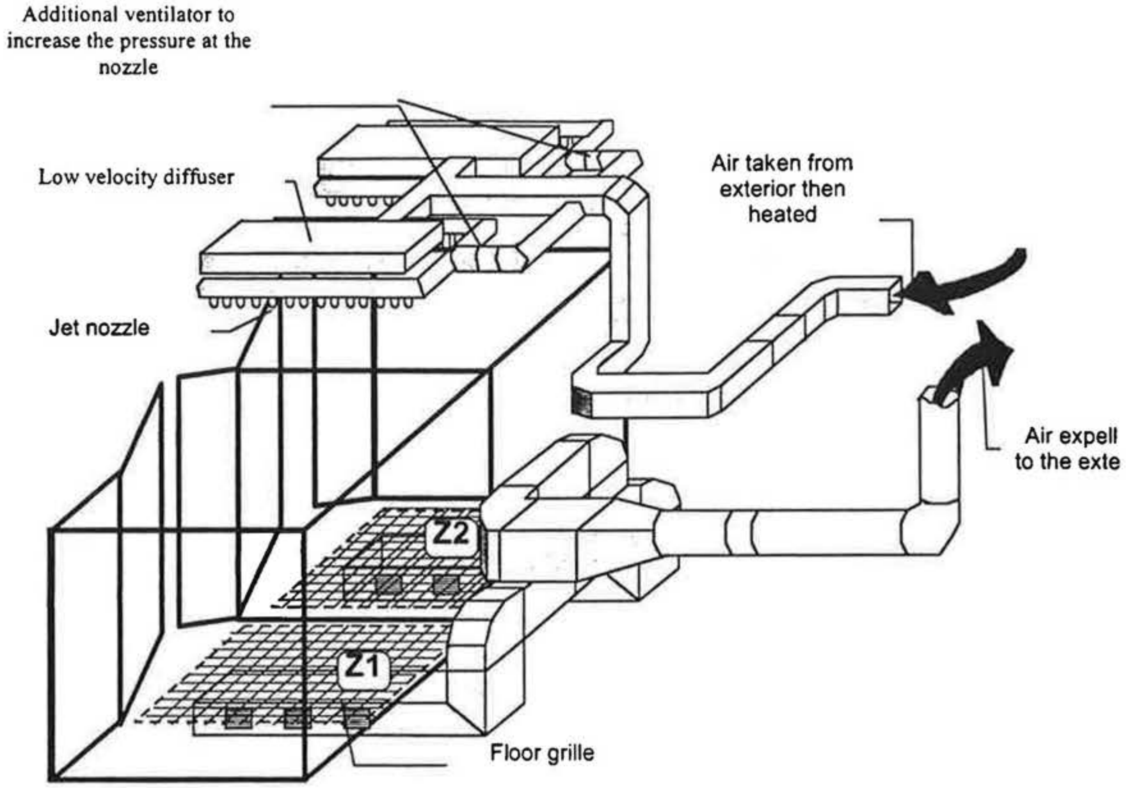

Figure 2 : diagram of the painting area and its ventilation installation

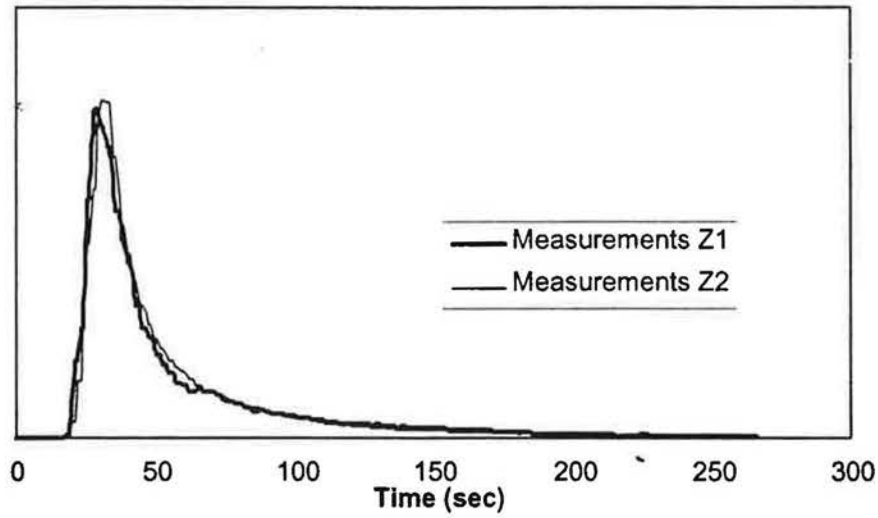

Figure 3 : the two response curves for zones Z1 and Z2 are similar. The title « normalised concentration » on the Y-axis indicated that the curves have been scaled so that the area below the curve is unitary

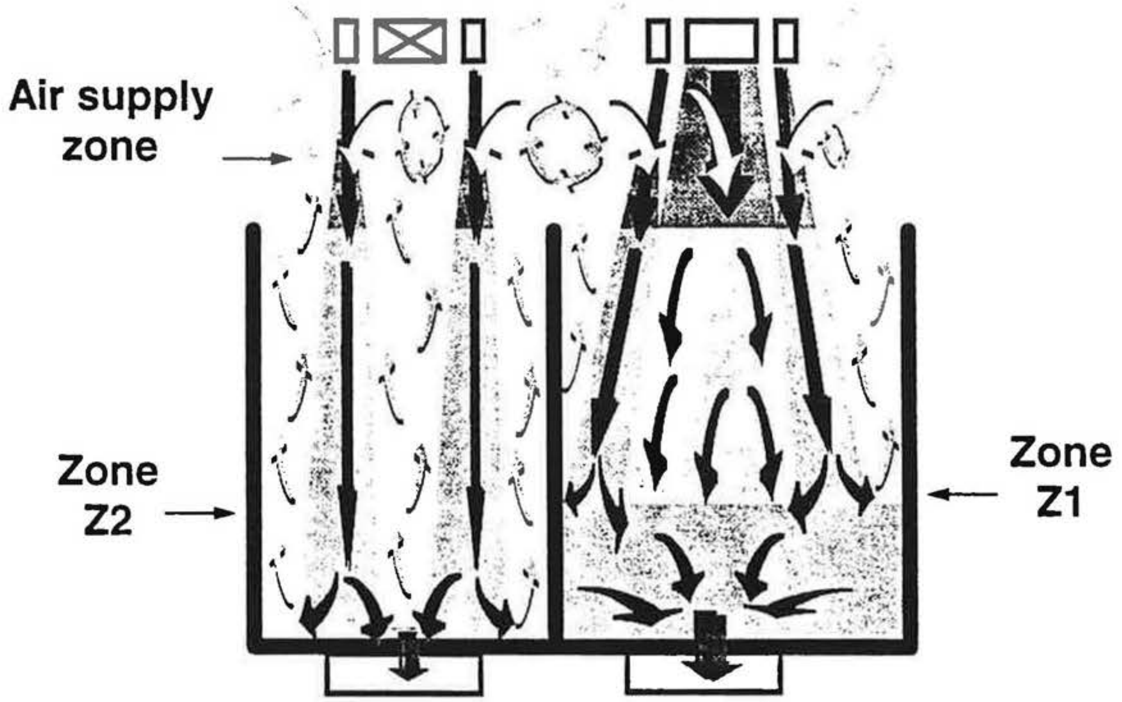

Figure 4 : the flow diagram is partially the result of a visualisation carried out with the smoke generator. The darker areas indicate piston-type organised flows whereas the lighter areas are agitated mixing-type areas

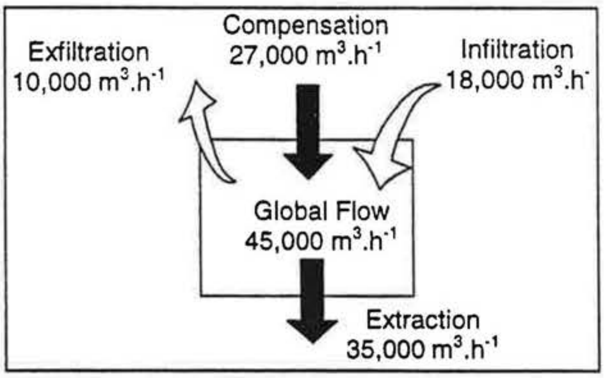

Figure 5 : summary of the flows entering and leaving the zone studied. The flow of 45,000 $m^3.h^{-1}$ was calculated from the dilution of the tracer injected into the compensation air

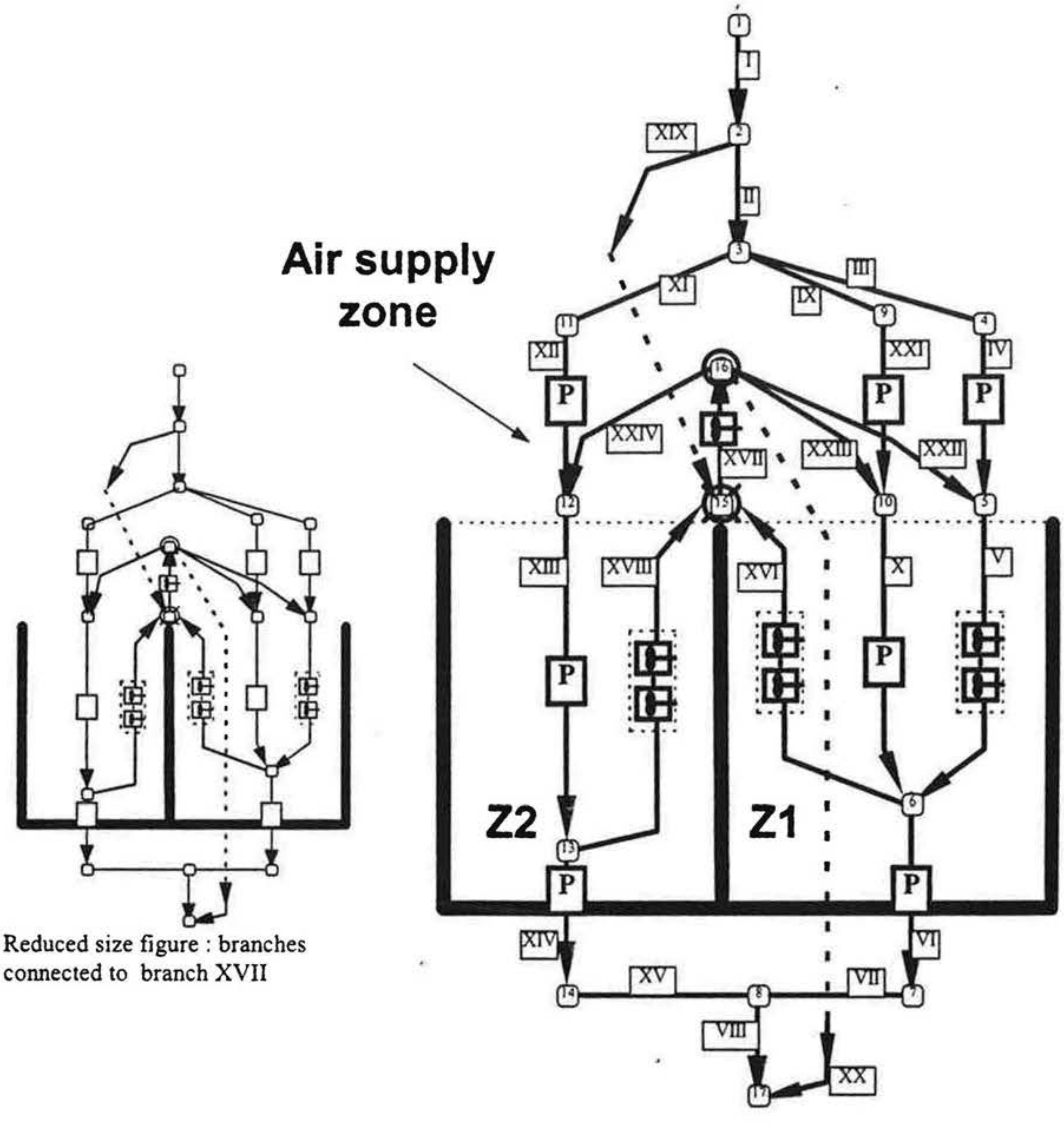

Figure 6 : network of modules representing the flow. The grey zone indicates the volume studied. The branches located outside represent the ducts as well as the air infiltration and exfiltration. They do not have a transfer function, and are there to ensure the conservation of the flows between the inlet and outlet of the network

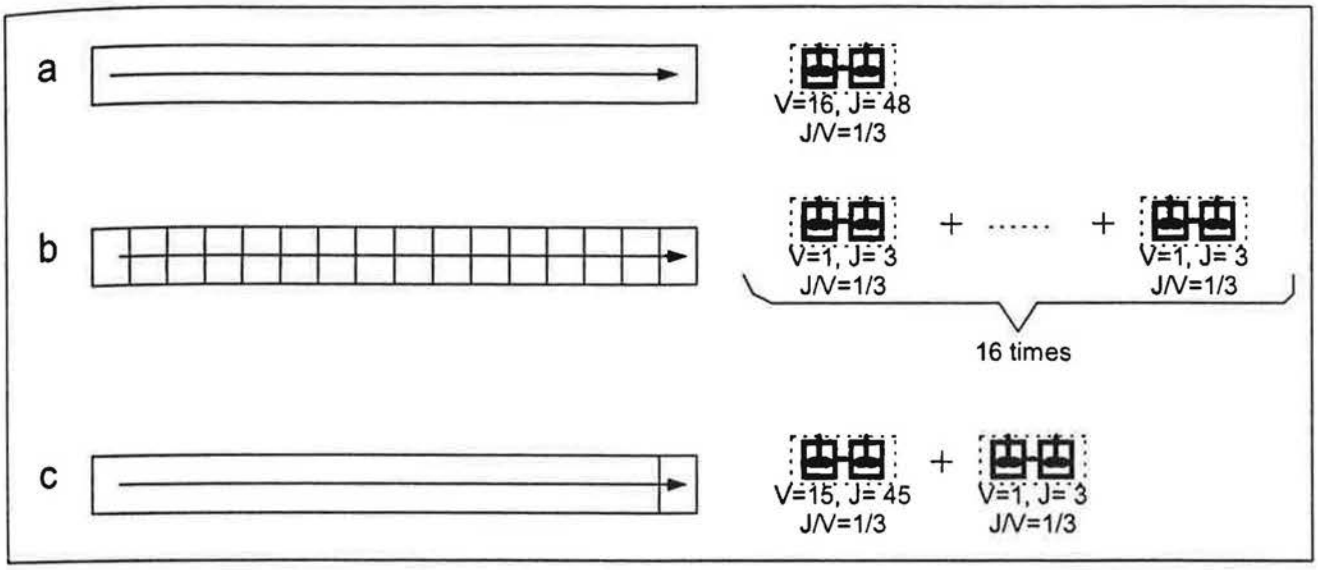

Figure 7 : three solutions for representing the same flow. The J/V constant allows those that are identical to be observed

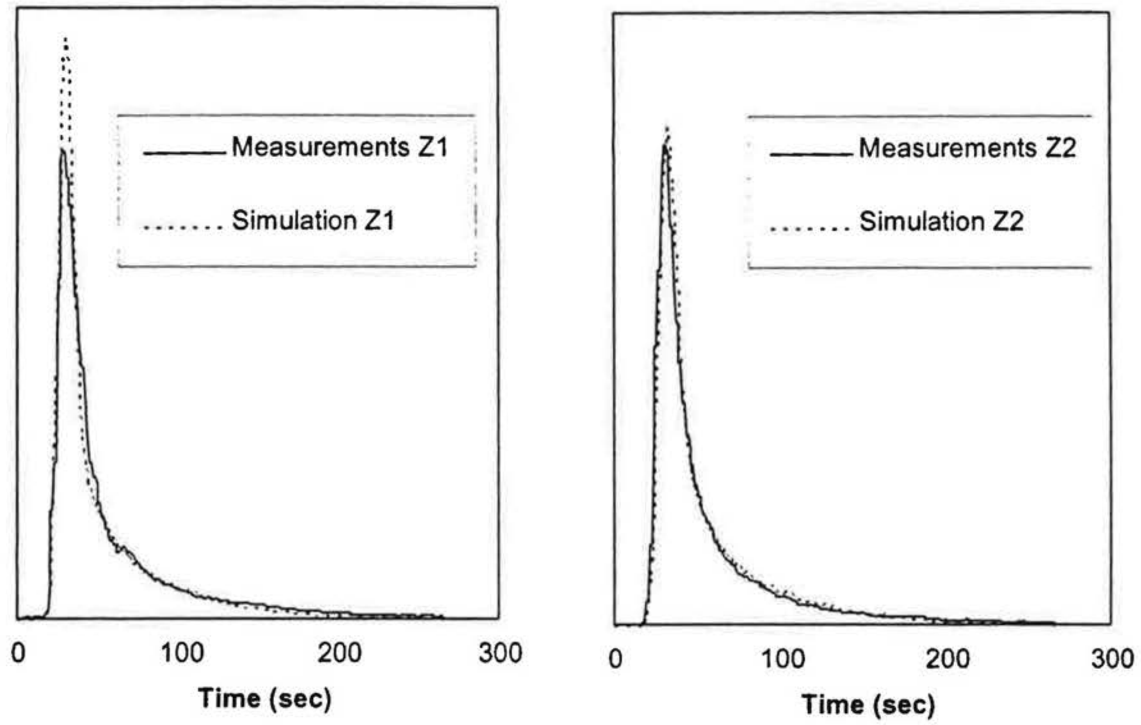

Figure 8 : comparison of the measured and simulated curves. By ignoring the fixed constraints, it would be technically possible to make the curves coincide better for side Z1.