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Measurement of Ventilation Effectiveness Parameters in an Electronics Factory.

J.R. Waters and C.E. Brouns

Coventry University, School of the Built Environment, Priory Street, Coventry CV1 5FB, United Kingdom

ABSTRACT

A very large electronics factory had been completely refurbished, and new mechanical ventilation systems installed. In an area of the factory where the principal activity was the bench assembly of small components, there were persistent complaints of eye nose and throat irritations, and absenteeism among the workforce was excessive. Careful examination of the environment had failed to identify any significant contaminants in the air. The situation was similar to the Sick Building Syndrome in office buildings. The problem was investigated by measurements of Ventilation Parameters, using the theory and techniques described in AIVC Technical Notes 28 and 28.2. Pulse, step-up, and decay measurements were carried out, and the results analysed to give air change efficiency, contaminant removal effectiveness, local air quality index, dosage index and transfer index. The results showed that the principal source of air entering the area was not the mechanical ventilation system. This made it difficult to interpret the values obtained for air change efficiency. However, the results for the contaminant removal parameters were consistent with the problems experienced by the workforce. The paper describes the difficulties of conducting ventilation effectiveness parameters in a complex industrial environment. Results are presented which show consistency in the determination of some parameters, and how these suggested solutions for this particular building.

INTRODUCTION

The electronics factory at New Horizon Park, Coventry was refurbished, and new mechanical ventilation systems were installed approximately two years ago. In an area of the factory where the principal activity is the soldering and bench assembly of small components, there were persistent complaints of eye nose and throat irritations, and absenteeism among the workforce was excessive. These problems began soon after the completion of the new ventilation system. Analysis of air samples taken from the environment did not identify any significant airborne contaminants. The situation appeared to be similar to the Sick Building Syndrome in office buildings.

A preliminary investigation revealed that other areas of the factory where similar production activities took place had also been refurbished at the same time, but there were no complaints in these other areas. Consequently the problem could not be associated with the production process, nor could it be associated with particular employees. The complaints were clearly specific to one particular area of the factory served by one air handling unit. The air handling unit itself and its associated ductwork were identical to those installed in other areas of the factory and seemed to be functioning normally.

In the absence of any obvious cause of the problem, an environmental survey was carried out. This included measurements of temperature and air velocity, but the main purpose of the survey was to measure the ventilation effectiveness parameters of the space.

DESCRIPTION of the INSTALLATION

Apart from the administration units, the factory is single storey throughout. Figures 1,2 and 3 show the general site layout, the area under investigation, and the layout of the air handling system. The problem area is approximately 50m x 11m, with one long side and one short side bounded by brick walls. The other two sides adjoin identical areas, each served by identical air handling units. The roof is a typical triangular construction with glazed northlights, but an open mesh "eggcrate" style suspended ceiling has been installed at a height of 3m above floor level. The volume of the problem area between floor level and ceiling level (the occupied zone) is 1568 m^3, and the volume of the roof void above the ceiling (the unoccupied zone) is 1228 m^3.

The air handling unit and the supply ductwork are mounted in the roof trusses above the suspended ceiling, and the sixteen air supply grilles are fitted flush with the ceiling. Return air passes up through the "eggcrate" ceiling, and flows along the roof space back to the air handling unit. The unit has separate supply and extract fans, and adjustable dampers which enable the proportion of recirculated air to be varied between 0% and 100%. The intake and exhaust for the unit are both at roof level. The design air flow capacity of the unit is 2.36 $m^3.s^{-1}$ with the fans at full speed. The unit also included a heating coil downstream of the supply fan, but no cooling coil.

INITIAL ANALYSIS

The expected air change rate with the fans at full speed and the dampers set to 0% recirculation is 5.4 air changes per hour, if it is assumed that the system ventilates only the occupied zone. The rate becomes 3.0 air changes per hour if the volume of the roof void is included. As there was a very low level of contaminant generation in the occupied zone, these air change rates should have been adequate. However, the placing of the ductwork supply terminals flush with the open "eggcrate" ceiling suggested that a proportion of the air flow from the terminals would short-circuit the occupied zone and go directly into the roof void, especially in winter when the supply air was heated. A preliminary analysis of this possibility was carried out by representing the problem as a two zone model, as shown in figure 4. The air flow from the terminals is assumed to be divided between zone 1 (the occupied zone) and zone 2 (the unoccupied zone) in a proportion, x, which can be varied. General buoyancy effects are included by means of an internal recirculation factor, y, of the fan supply rate. Recirculation within the air handling unit can be included by means of a factor, r. This leads to the following equations for the interzone flows.

$$F_{01} = (1-x)(1-r)Q$$
$$F_{02} = x(1-r)Q$$
$$F_{10} = 0$$
$$F_{12} = (1-x)(1-r)Q + rQ + yQ$$
$$F_{20} = (1-r)Q$$
$$F_{21} = rQ + yQ$$

where F_{ij} is the flow from zone i to zone j, and i=0 corresponds to outside air. This model was used to compute Ventilation Effectiveness Parameters for a range of values of x, and for r=0 (full fresh air) and r=0.5 (50% recirculation). The most useful parameters [1,2] are the Local Mean Age of Air, the Local Air Change Index, and the Local Air Quality Index, the last of these being evaluated for contaminant injected in zone 1 only. Figure 5 shows plots of these parameters against the variable x.

Several matters of interest arise from figure 5. The point of intersection of the lines on the Local Air Change Index graph occurs at approximately x=0.44, which is the value of x when the flow rate into the zones is proportional to their volume. There is a similar intersection on the Local Mean Age graph. Both these graphs confirm the expected decline in the fresh air provision in the occupied zone as the proportion of the output from the supply terminals going into the upper zone increases. Additionally they show that below x=0.44 recirculation, either via the air handling unit or by buoyancy effects, worsens the provision, whereas above x=0.44 it improves it. Paradoxically, therefore, if it happens that x>0.44, increasing the fresh air intake into the air handling unit by reducing its recirculation setting will actually make things worse. The Local Air Quality Index graph leads to a similar conclusion, except that the worsening is true for all x>0.

MEASUREMENTS

The measurement programme covered the period from the 11th to the 22nd of November 1991 inclusive. For measurement and analysis purposes, the total space was considered as four zones. In the occupied space below the ceiling, three zones of equal volume were defined, and the space above the ceiling was defined as a single zone. Figure 3 shows the layout of the ventilation system and the zones. Tracer gas sampling points were placed approximately at the centre of each zone, and also in the supply and return ducts of the air handling unit. Step-up tests were carried out by injecting tracer gas (sulphur hexafluoride) into the air immediately upstream of the supply fan. The tracer gas concentrations following switch-off of the tracer were treated as decay measurements. Pulse tests were carried out by injecting a short burst of tracer into one of the zones.This was repeated for each of the three zones in the occupied space. The tracer gas concentration curves were analysed using software based on the usual Ventilation Effectiveness theory [1,2]. The three types of test, step-up, decay and pulse were analysed as follows.

1. Step-up tests

For the first set of step-up tests, the rise in the tracer gas concentration in the return duct followed very closely the rise in the inlet duct, and was ahead of the rise in the four zones. This caused some surprise, and led to a close inspection of the air handling unit. It was discovered that the indicator on the outside of the unit, which was showing 0% recirculation (or full fresh air) was exactly the wrong way round. In other words, the system was set to 100% recirculation, so that contaminated air was being fed back into the ductwork. The rapidity of the rise in the return duct suggested also that there was some short-circuiting of air from the supply side to the return side. The fact that the system was on 100% recirculation was known to the maintenance engineer, who explained this setting as being necessary to both conserve heating energy and to prevent complaints of low temperatures from the operatives. The 100% recirculation setting made the analysis of the step-up tests largely meaningless.

2. Decay tests

These were used to establish the average air change rate of the space. This is valid because the ventilation system maintains stirring of the air throughout the decay process. The time constant over a series of tests ranged from about 28 minutes to about 40 minutes. This represents air change rates of between 1.5 and 2.1 air changes per hour. However, this cannot all be fresh air, and most of it must have come from other areas within the factory. One test with the system set to 100% fresh air yielded an air change rate of between 3.3 and 3.9 air changes per hour. This test also gave values for the Local Mean Age and the Local Air Change Index of the air in the zones.

Table 1 - Local Mean Age and Local Air Change Index

Zone	Local Mean Age (minutes)	Local Air Change Index
1	23	0.79
2	16	1.13
3	9	2.01
4	21	0.86

3. Pulse tests

These were used to derive the local mean age of the contaminant and the total dosage index. The averages and standard deviations derived from several sets of measurements are shown in the following tables.

Table 2 - Local Mean Age of Contaminant, minutes

Zone of Injection	Zone of Measurement 1	2	3	4
1	22 ± 5	29 ± 3	43 ± 8	21 ± 2
2	21 ± 2	16 ± 3	40 ±23	19 ± 3
3	31 ± 4	22 ± 4	14 ± 4	26 ± 6

Table 3 - Total Dosage Index, vpb.hrs/ml

Zone of Injection	Zone of Measurement 1	2	3	4
1	0.255±0.072	0.114±0.007	0.111±0.062	0.191±0.022
2	0.165±0.075	0.244±0.137	0.125±0.125	0.157±0.090
3	0.092±0.077	0.090±0.043	0.175±0.088	0.071±0.059

The Local Air Quality Index can be derived from the Total Dosage Index for a pulse test by means of the equation

$$\varepsilon_p^c = \frac{V_{cp}}{Q.D_p}$$

where D_p is the Total Dosage Index due to a release of a volume equivalent of contaminant V_{cp}. Using the median of the results of the decay tests gives the effective fresh air supply rate, Q, as 1.4 $m^3.s^{-1}$. The values in Table 3 were used to construct Table 4.

Table 4 - Local Air Quality Index

Zone of Injection	Zone of Measurement 1	2	3	4
1	0.78	1.74	1.79	1.04
2	1.20	0.81	1.59	1.26
3	2.16	2.20	1.13	2.79

SIMULATIONS

From the results of the experimental measurements, an intuitive estimate was made of the most likely flow rates between the zones of the four zone model. These flows, which are shown in Figure 6, were entered into the multi-zone air movement model, in order to compute theoretical values of the Local Mean Age of the Contaminant, the Total Dosage Index, and the Local Air Quality Index. Tables 5,6 and 7 show the results.

Table 5 - Local Mean Age of Contaminant, minutes

Zone of Injection	Zone of Measurement 1	2	3	4
1	21	41	43	38
2	37	20	38	37
3	44	34	16	34

Table 6 - Total Dosage Index, vpb.hrs/ml

Zone of Injection	Zone of Measurement 1	2	3	4
1	0.418	0.122	0.079	0.152
2	0.170	0.330	0.093	0.157
3	0.097	0.116	0.231	0.130

Table 7 - Local Air Quality Index

Zone of Injection	Local Air Quality Index of Zone 1	2	3	4
1	0.39	1.34	2.08	1.08
2	0.96	0.50	1.75	1.04
3	1.68	1.41	0.71	1.26

DISCUSSION and CONCLUSIONS

Inspection of the measured results shows that in many cases the standard deviations were large. This was not surprising, as the buoyancy of the air leaving the terminal units would have varied with both the weather conditions and the cycling of the heating coil. In general, the results from individual tracer gas tests within each set tended to produce values in the same rank order, again suggesting that the large standard deviations were due to real changes in the performance of the installation rather than excessive experimental error.

With the air handling unit on its usual setting of 100% recirculation, the measured air change rate of between 1.5 and 2.1 ach could be entirely accounted for by air exchange with other parts of the factory. This means that the area received no direct fresh air, that is all incoming air was stale air. In practice, some fresh air would have entered the area from the external door at one end, and by leakage through the structure. With the unit on 100% fresh air, a rate of between 3.3 and 3.9 ach is consistent with the fan rating, which taken by itself would have given 3.0 ach. The extra could be due to leakage and exchange with adjacent areas.

When the system was tested on 100% fresh air, the results for the Local Mean Age and the Local Air Quality Index suggest that the distribution of fresh air was poorest to zone 1, where the majority of the complaints occurred.

The results of the pulse tests show that the Dosage Index for each zone due to a contaminant released within itself is highest for zone 1, next highest for zone 2, and lowest for zone 3. The same is true for the Local Mean Age of Contaminant. This is consistent with a high rate of complaint from the occupants of zone 1. The Local Air Quality Index is lowest in zone 1, next lowest in zone 2, and highest in zone 3, which is also consistent a high complaint in zone 1.

The results for the simulations carried out on the four zone model of the installation show that some of the individual values are very close to their measured counterparts, whereas some differ by a substantial factor. Nevertheless the results of the simulations show the same trends as the measurements, and hence confirm the poor ventilation of zone 1.

The overall conclusion is that the measurement of ventilation effectiveness parameters in a complex environment has provided definite evidence to support and explain a problem which had otherwise been evident only from the subjective responses of the occupants. In this particular instance, the contaminant removal effectiveness parameters have been the most helpful in identifying and quantifying the problem. The use of zonal models has also been of benefit in this case. The initial analysis using the two zone representation showed that there was likely to be a potential problem, and the four zone model, assembled from information on the fan rating and from the evidence of the measurement programme, was useful in confirming the conclusions, and also in giving an indication of the probable air flow patterns. The solution for this installation appeared to be relatively simple, namely to reduce the recirculation setting of the air handling unit.

REFERENCES

1. "A Guide to Air CHange Efficiency", AIVC TN28, 1990
2. "A Guide to Contaminant Removal Effectiveness", AIVC TN28.2, 1991

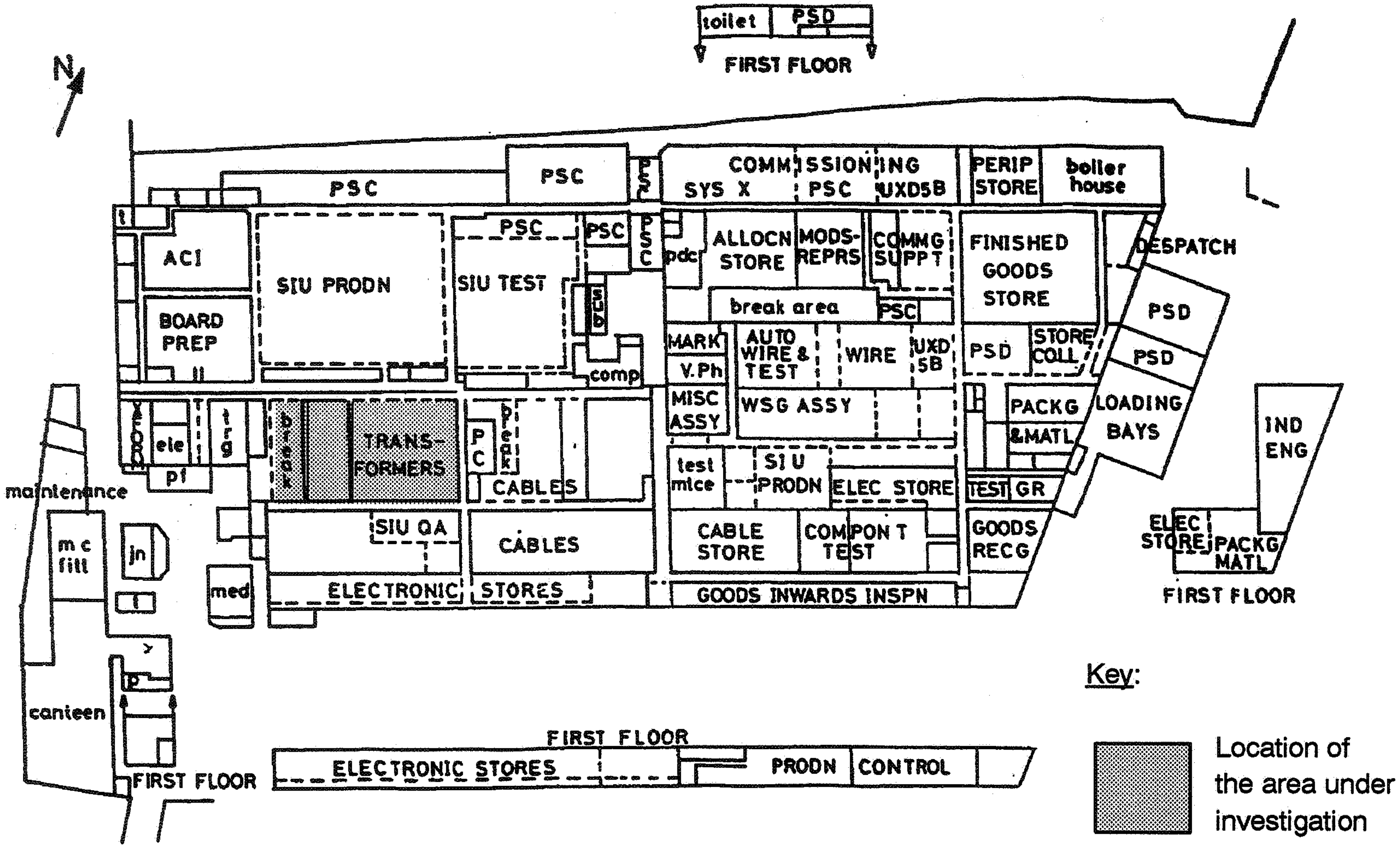


Figure 1 - Site Plan

Figure 2 - Area under investigation.

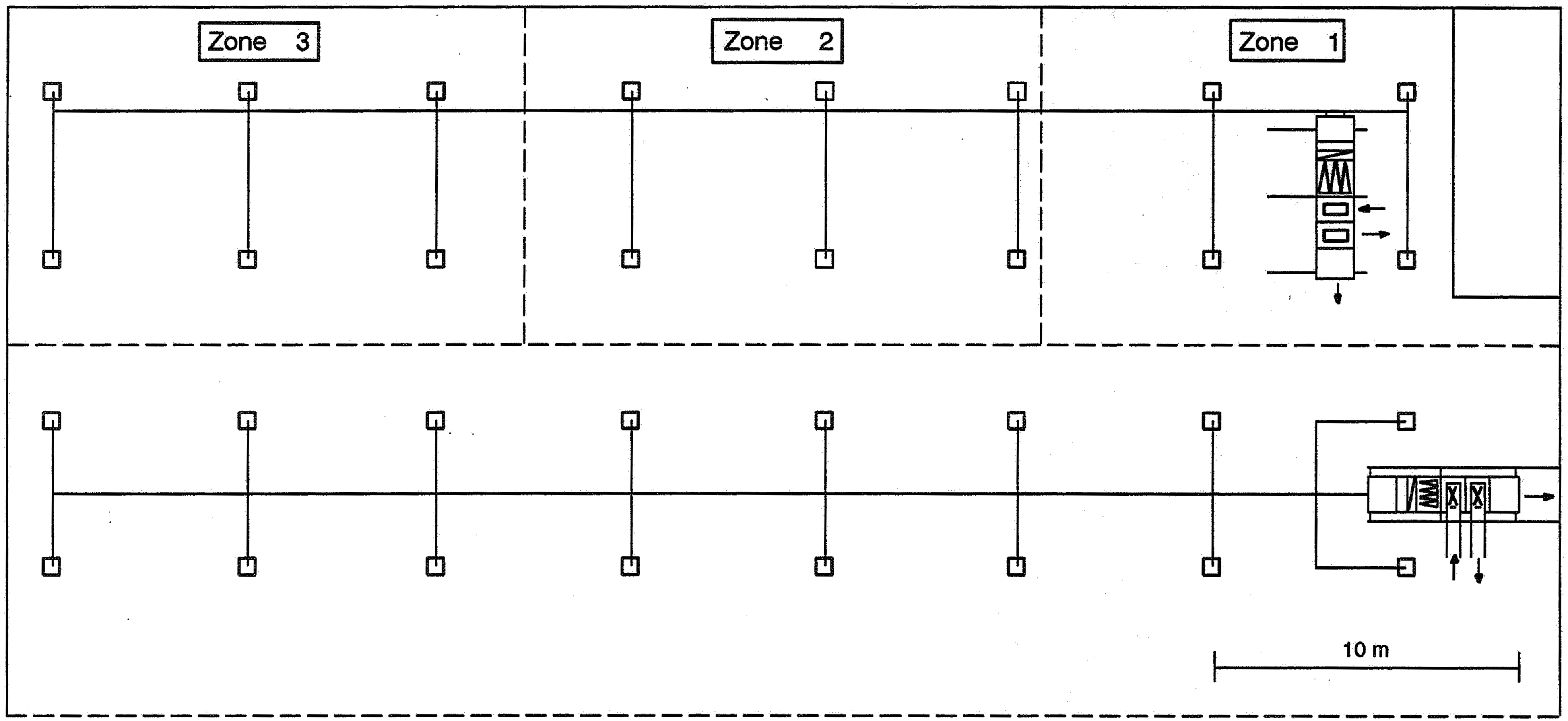


Figure 3 - Layout of the Heating and Ventilation System.

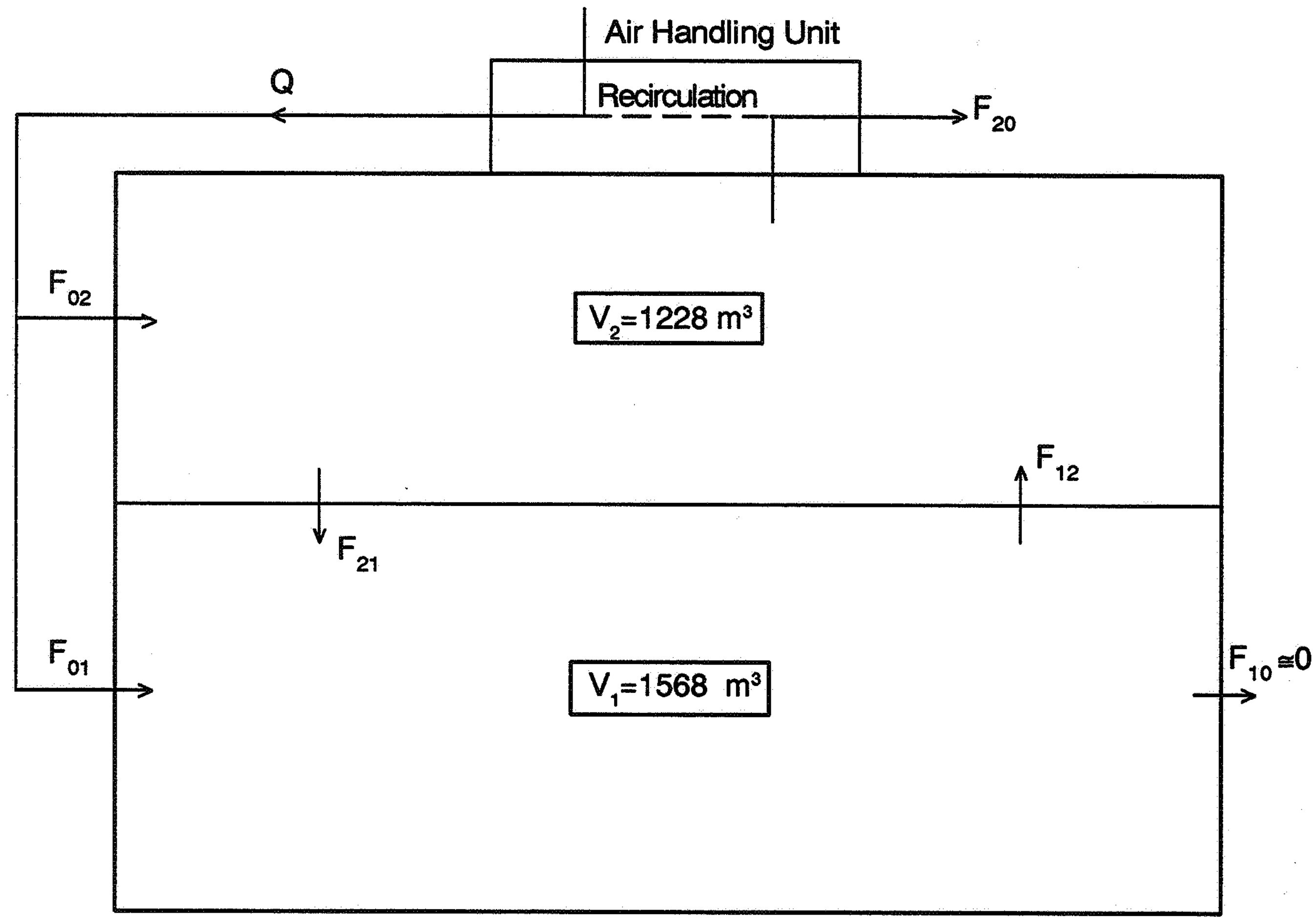


Figure 4 - 2 Zone Model.

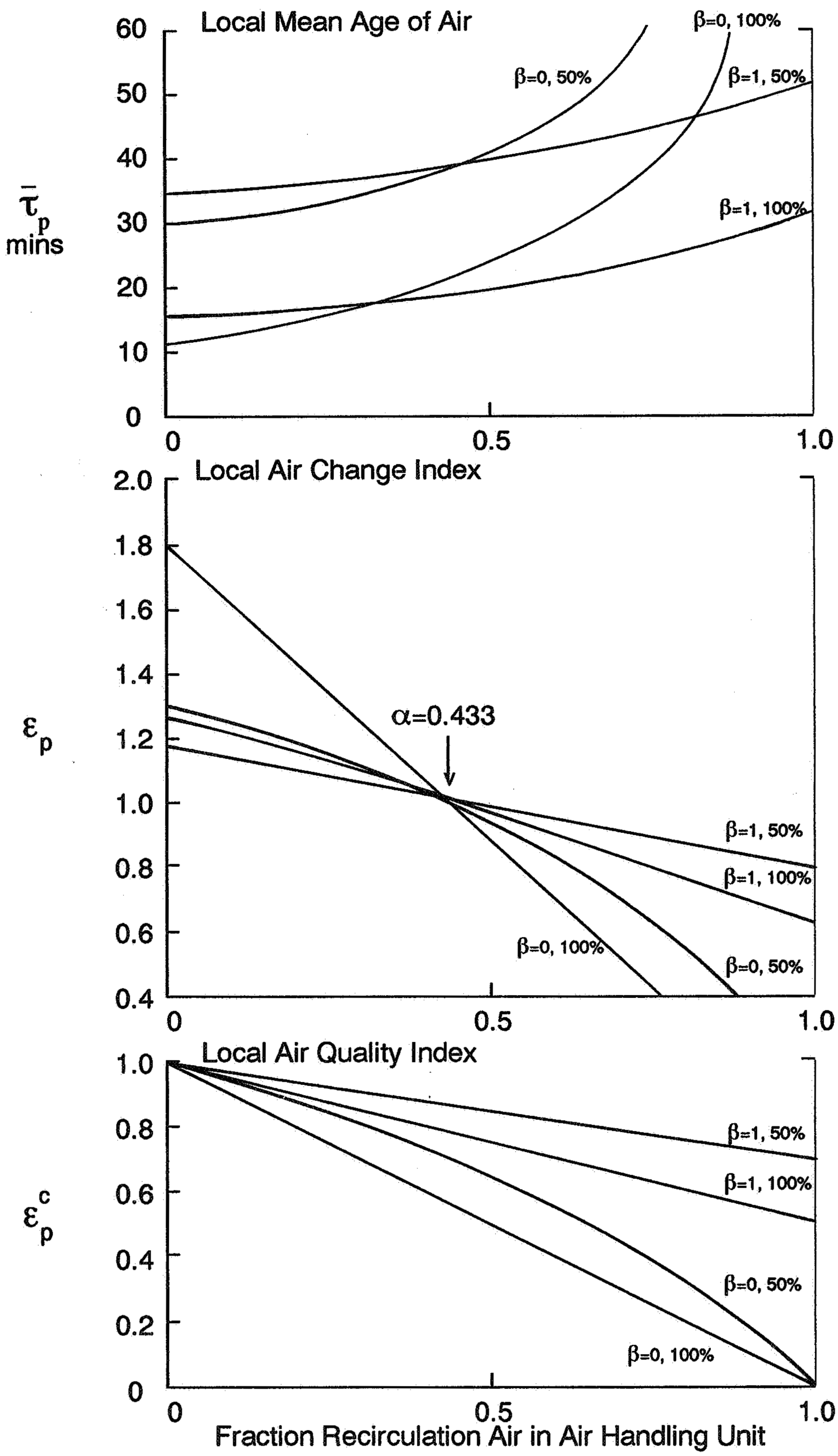
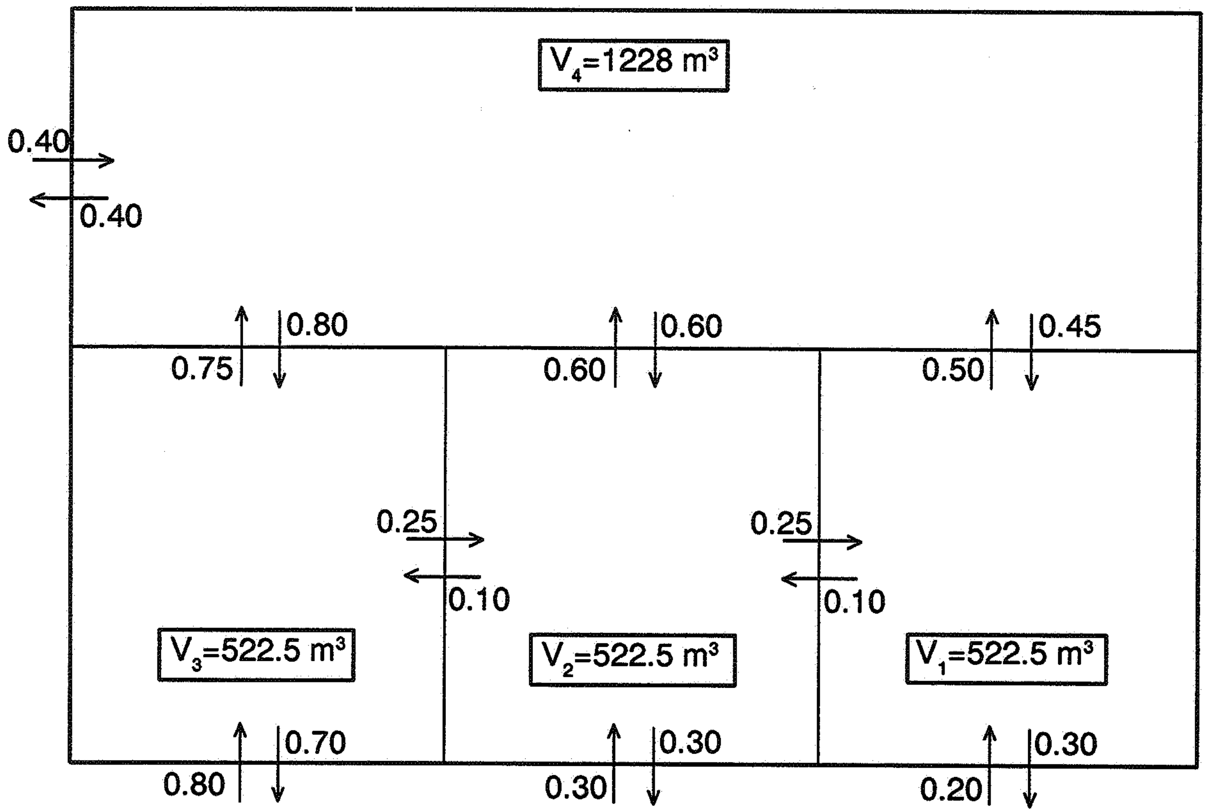


Figure 5 - Results of the 2 zone model.



Please note that all the air flow rates in the above figure are expressed in m^3/s.

Figure 6 - 4 Zone Model.