High Performance Displacement Ventilation Using Fabric Diffusers –A Case Study

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Summary

Ventilation is an essential system in buildings required to maintain a healthy and productive indoor climate. Meanwhile, the essential pursuit of the climate change agenda also requires that detail consideration be given to system energy performance.

Designing a displacement ventilation system based upon an ASHRAE prescriptive standard for a conference and restaurant complex with smoking permitted, provided a challenge to the design team. The use of fabric diffusers offered the benefits of high volume air supply capacity without infringing upon noise and thermal comfort criteria.

This paper discusses the issues explored during the design, presents the results of a comparative air quality and energy analysis between the displacement ventilation system and a conventional dilution ventilation system. The paper goes onto discuss some of the problems encountered during and after commissioning and describes the use of Computational Fluid Dynamics (C.F.D.) in diagnosing the problems.

Introduction

The indoor climate must meet the needs of the occupants for a healthy, safe and productive environment. Air and Radiant temperature criteria, air movement and asymmetric inbalances must fall within limits. The other major influence on comfort and in particular health is the Indoor Air Quality (IAQ). It is an often-quoted fact that in the industrial world we spend on average 90% of our time in buildings. In the USA poor indoor air quality (IAQ) has been estimated to result in costs in the region of $17 billion -$43 billion[i] annually in healthcare and lost productivity. If applied simplistically to the UK on a pro-rata GDP basis this is equivalent to £1.6 billion to £4.0 billion per annum.

Ventilation is too often seen as an expensive and environmentally detrimental option particularly in terms of its consumption of energy and the consequent CO_2 emissions. It involves moving large quantities of outdoor air that must be heated, or cooled, filtered and sometimes humidified or dehumidified. Nevertheless the difficulties of providing a high IAQ environment at minimal costs should not be used as a reason to reduce the criteria but rather should be seen as a challenge to designers to cut the energy consumption without compromising the aim of producing a healthy invigorating indoor climate. The capital and running costs should be considered in the light of the health & productivity benefits arising from improved IAQ.

Dynamic Thermal analysis software allows us to perform many fundamentally simple calculations. By defining an operational system characteristic and using recorded weather data, energy flows can be calculated and summarised over the year. In this way different system can be compared.

The basis upon which we design our systems naturally tends to lag behind the technology and techniques actually in use in the industry. Standards ought to give sufficient flexibility to accommodate the differences in performance between systems. The blunt use of prescriptive standards too often leads to unnecessary expenditure and technical problems.

Basis Of Comparison

A restaurant/conference facility was used as the basis for the comparison. The room configuration and dimensional information is shown in Figures No.1 to 3 and the design parameters are listed in Table No.1.

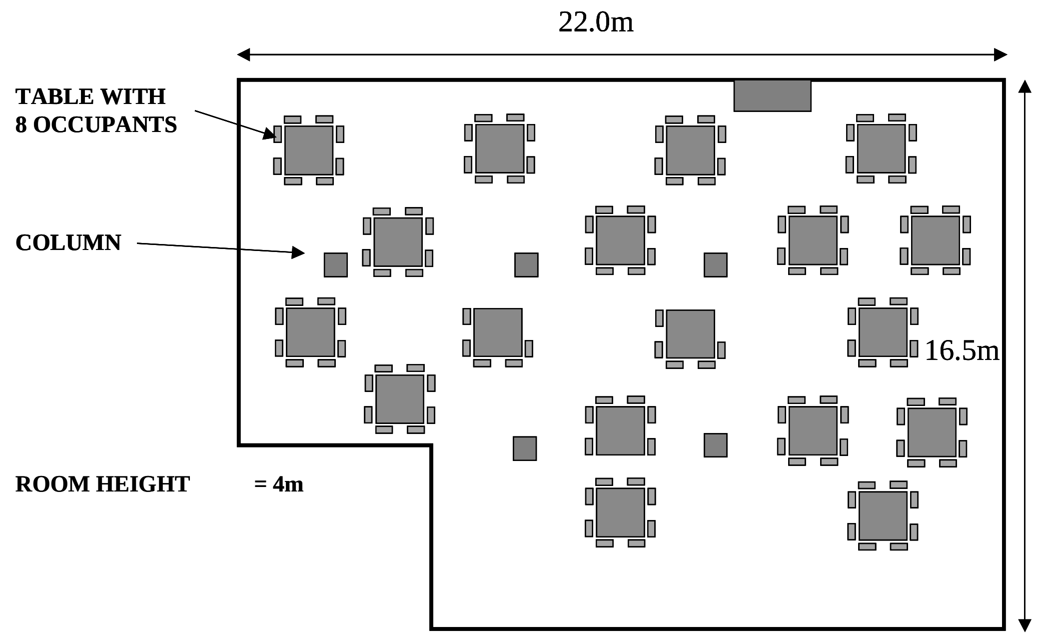


Figure 1 – Plan Occupant layout

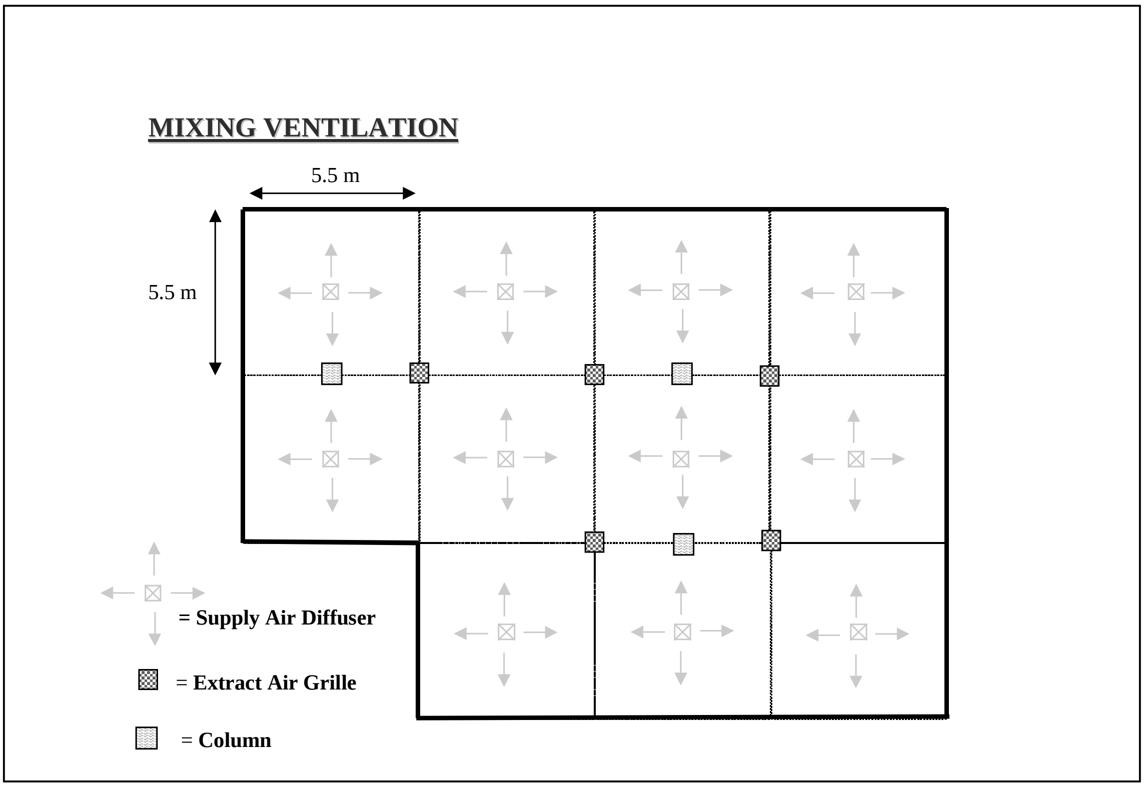


Figure No.2 : Plan –Mixing Ventilation Scheme

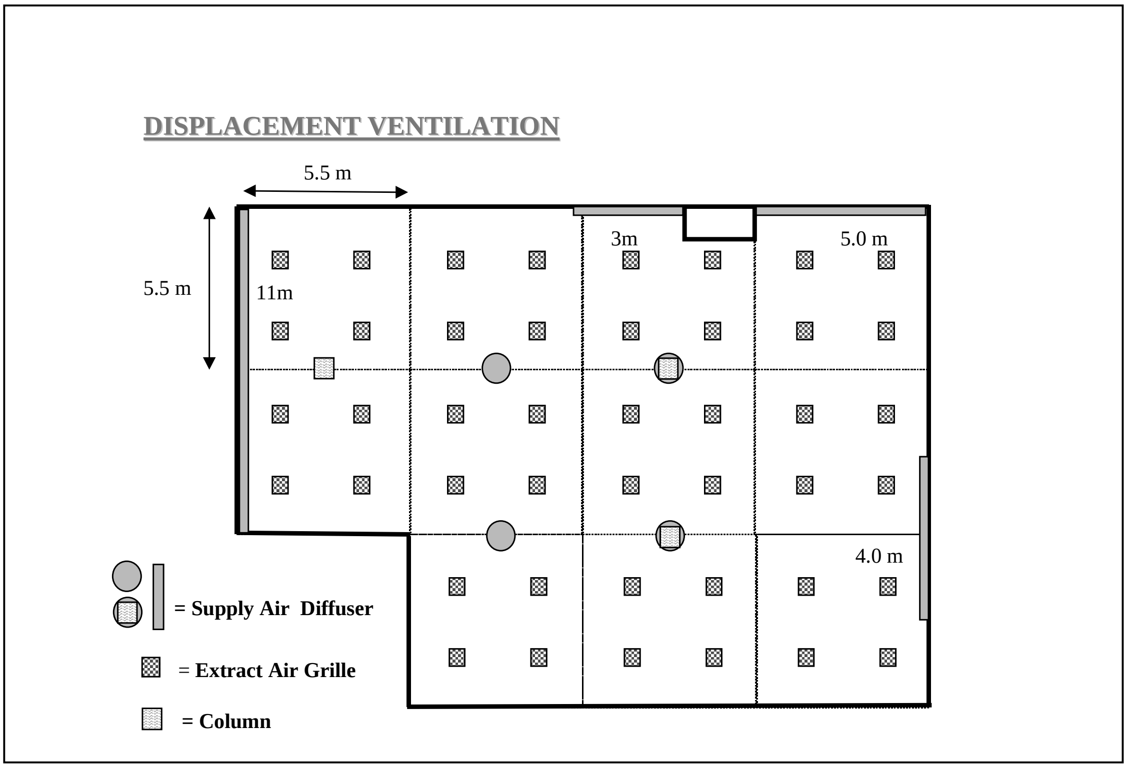


Figure No.3 : Plan –Displacement ventilation Scheme

Three separate models were analyzed. The volume flow rate of each system was determined by the fresh air requirement or by the cooling load whichever the greater. The displacement ventilation system was based on a fresh air allowance of 15 Litres/second/person (L/s/p) (DV) supplied at 19^{o}C.

The first mixing ventilation model (MV(A)) had a volume flow rate based on the cooling load with a supply temperature of 16.2^{o}C and with a fresh air volume flow rate based on the CIBSE minimum fresh air allowance of 8 (L/s/p). The second mixing model(MV(B)) was based on 20L/s/p, a value chosen to provide similar indoor air quality to the displacement system with 15L/s/p

The air handling unit schematic is shown in Figure No.4. The configuration and control of the air handling systems determine the overall energy consumption. Each model had identical components operated to deliver air at the design condition. Each unit incorporated exhaust air adiabatic cooling, a cross plate heat exchanger and cooling and heating coils. The cooling coil was configured to operate as Face and Bypass in order to minimise cooling load.

Two Displacement Ventilation systems were analysed, a constant volume system (DV(A)) and a Demand led Displacement Ventilation (DDV) system (vDV(A). Alternative Dilution Ventilation mixing systems were set up to operate in a constant volume mode (MV(A)) for CIBSE minimum rate of ventilation, and MV(B) where the rate is increased in order to approach an IAQ that is comparable with a Displacement Ventilation System. Further comparison is made between the models operating in a variable volume mode (vMVa or b and DV). In practice the mixing system would require variable geometry diffusers to operate effectively in a variable volume mode and would not be able to operate over the volume flow rate range of the DDV system. The minimum volume flow rate of the mixing system is therefore taken to be 40% of the maximum.

	MIXING			DISPLACEMENT		
	MODEL 'A'		MODEL 'B'			
	MV(a)	**vMV(a)**	**MV(b)**	**vMV(b)**	**DV**	**vDV**
Total delivered volume flow rate	2.7 m^3/s	2.7 m^3/s	2.7 m^3/s	2.7 m^3/s	2.3 m^3/s	2.3 m^3/s
Minimum Supply air volume flow rate	-	1.08	-	1.08	-	0.27
Fresh air provision L/s/person	8 [ii]	8	20	20	15	15
Percentage fresh air	60 %	60 %	100%	100%	100%	100%
Minimum Supply air temperature	16.2^{o}C	16.2^{o}C	16.2^{o}C	16.2^{o}C	18^{o}C	18^{o}C

ROOM THERMAL LOADS			
People	134	90 W/person	45% Radiant
Lighting		20 W/m^2	43% Radiant

TABLE NO. 1 DESIGN PARAMETERS

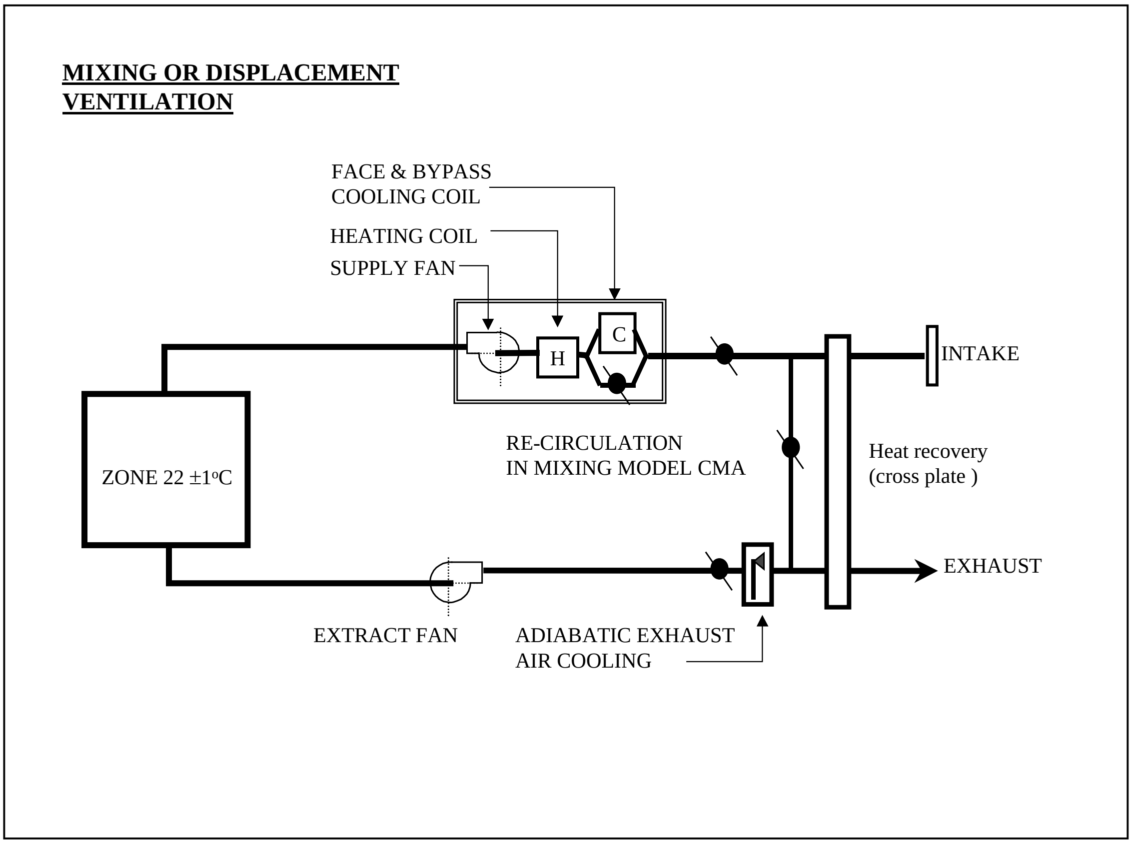
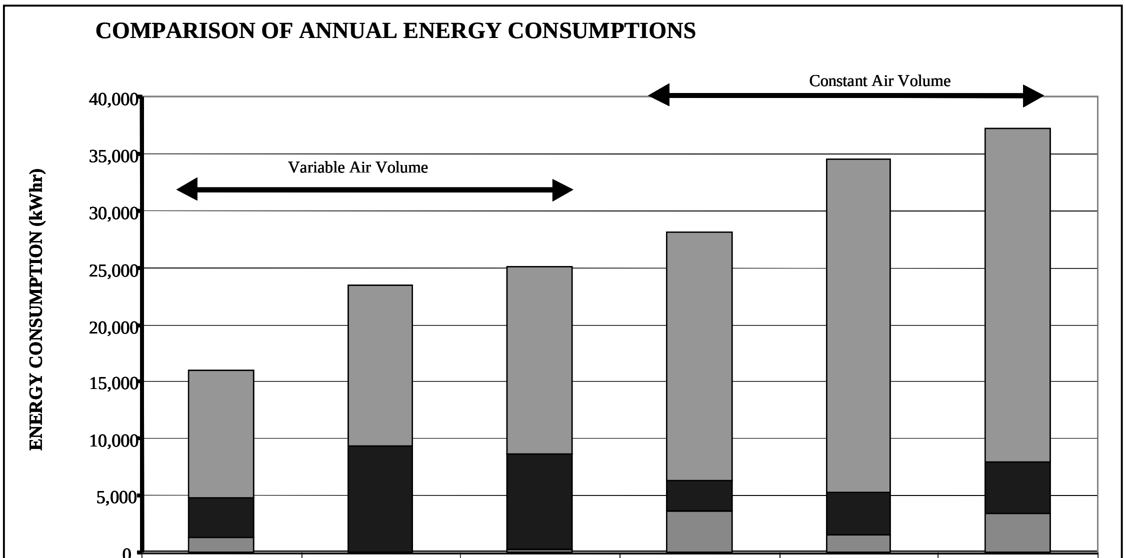


Figure No.4:- Ventilation System Schematic

Results

The dynamic analysis results are presented in Figures 5 & 6 and show annual energy consumption and CO_2 emissions apportioned between fan energy, cooling and heating. The results highlight the benefit of a demand led variable air volume system. The Displacement Ventilation system shows further benefits over a mixing system including a greater turndown ratio. The overall reduction in the amount of air delivered into the room over the year also leads to a proportionate reduction in heating and cooling energy consumption. The increased return air temperature in the DV system resulting from room air stratification increases the heat recovery potential and hence offsets the increase in heating demand that otherwise would arise from the greater outdoor air volume of the Displacement ventilation System.



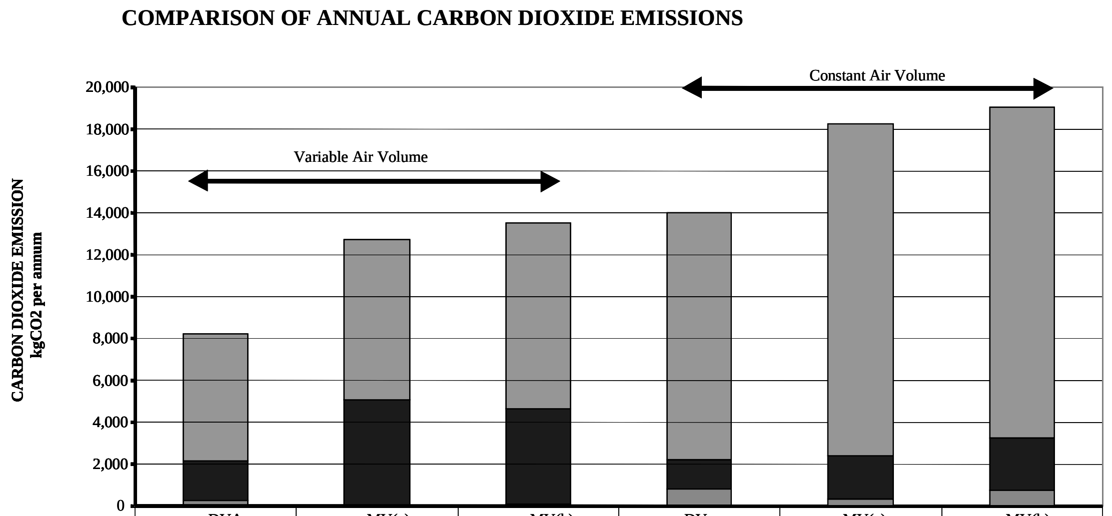
	vDV	vMV(a)	vMV(b)	DV	MV(a)	MV(b)
Fans	11217	14145	16464	21805	29291	29291
CHILLER	3487	9271	8407	2626	3758	4585
HEATING	1271	11	231	3624	1508	3365

Figure No.5: Energy Consumption Comparison

The cooling energy consumption is decreased in comparison with a mixing system since the outdoor air need only be cooled to 18^{o}C compared to an assumed off coil temperature of 15^{o}C of the mixing system.

Figure No. 6 shows the CO_2 emissions that follow the same pattern as the energy consumption since the source is predominantly electricity. An overall reduction of approximately 11,000 kg/annum is achieved by using a Demand led Displacement Ventilation (DDV) system compared to a conventional Constant Volume Mixing Volume system.

Figure No.6: Carbon Dioxide Emissions



	vDVA	vMV(a)	vMV(b)	DV	MV(a)	MV(b)
Fans	6057	7638	8891	11775	15817	15817
CHILLER	1883	5006	4540	1418	2029	2476
HEATING	267	2	49	761	317	707

MODEL VARIANT

A number of different comparisons can be made between the various models and these are summarised in Table No.2.

		PERCENTAGE ANNUAL		
Models compared	**Change in model**	**Energy consumption reduction (%)**	**Carbon dioxide emissions reduction (%)**	**Comments (based on cfd analysis)**
MV(b)/MV(a)	Reducing Fresh air allowance	7	4	Decrease in Indoor Air Quality (IAQ)
MV(b)/DV	Changing from a mixing to a displacement ventilation system	25	27	Improved IAQ
DV/Vdv	Applying demand led variable air volume	43	41	Improved System thermal performance
MV(b)/vDV	Constant volume full fresh air Mixing ventilation to demand led displacement ventilation	57	57	Improved IAQ and thermal performance

Table no. 2 –Predicted Benefits Of Displacement Ventilation

Overall the analysis a demand led displacement ventilation system would yield savings of 57% when compared with a conventional mixing ventilation system and produce a higher IAQ for the occupants.

The Computational Fluid Dynamics (CFD) results are presented in Figures 7 & 8. Figure 7 shows the relative CO_2 concentrations between the three models. The full fresh air models achieve control within this criteria in the occupied zone. The minimum fresh air mixing model fails to maintain conditions. This can be attributed directly to the re-circulation at the Air Handling unit.

The Local Mean Age of Air (Figure 8) shows times of 7 to 9 minutes in the occupied zone for mixing system compared to 2 to 8 minutes for a displacement system. Again the plume around the occupants has the effect of providing air to the occupant-breathing zone with a mean age of 2.5 to 3 minutes. The implication is that the shorter the air is in the room the less the absorption of the room pollutants and the higher the IAQ.

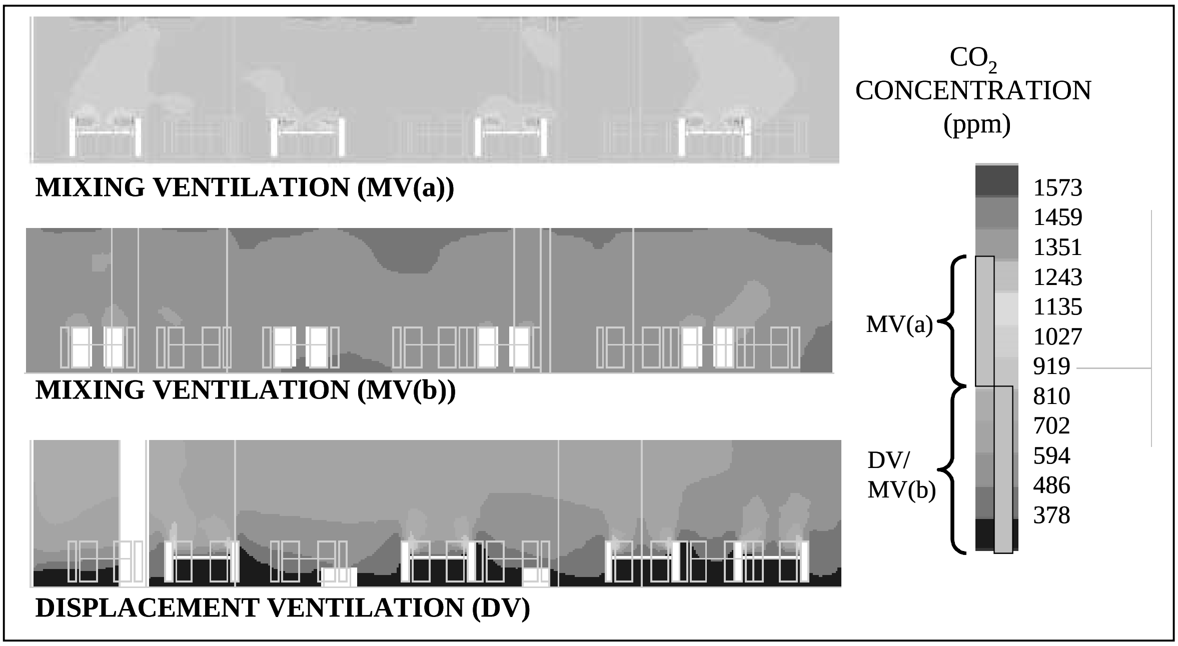


Figure No.7: CFD Results –CO_2 Room Concentrations

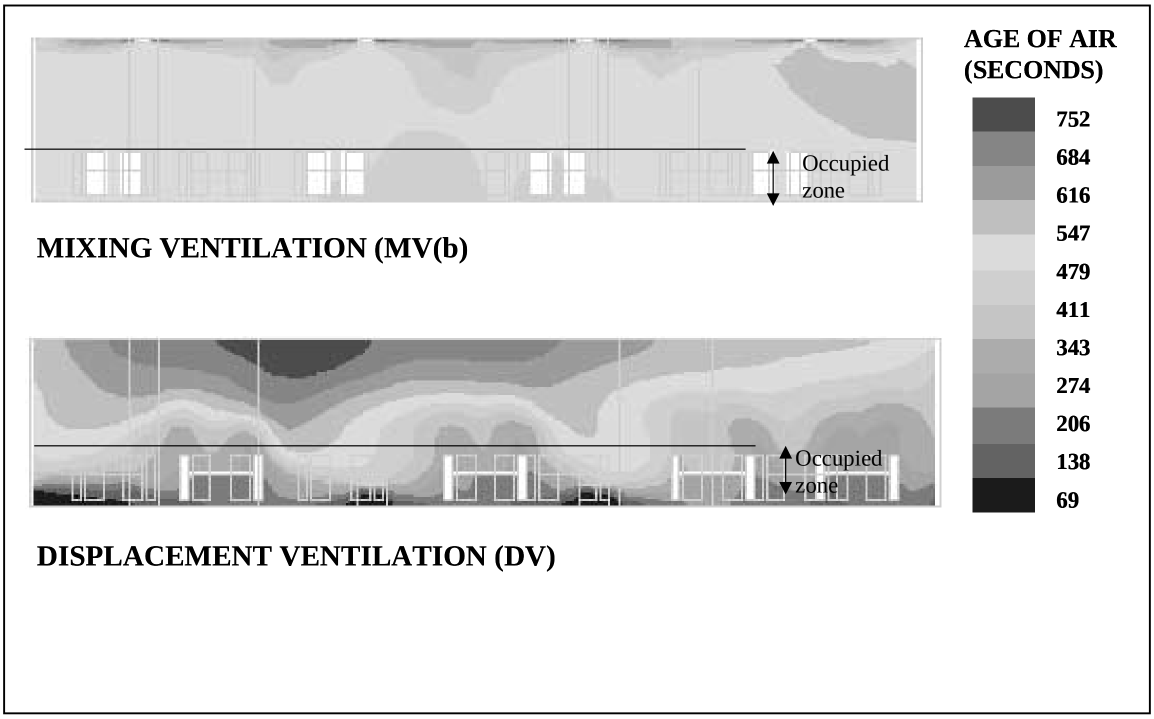


Figure No.8: Age of Air –Room Variations

In summary the analysis showed that:

1. Cutting back the fresh air content of the supply air is seen to yield the smallest energy saving benefit whilst compromising the IAQ.
2. Changing from a dilution mixing system to a displacement ventilation system yields savings of 25% in energy consumption.
3. Operating a displacement ventilation system on a variable volume basis compared with a constant volume basis yields further savings of 43%.

Fabric Diffuser

The decision was taken by the design team at the client's request to provide a fresh air ventilation rate in compliance with the minimum requirements for a smoking lounge as set out in ASHRAE 62-R[iii] – 30 litres/second per person (l/s/p).

Introducing air into a densely occupied space at a rate equivalent to 13 l/s/m^2 (18ach^{-1}) would create problems with a conventional system and this was the case for the displacement ventilation system. These problems were compounded by restrictions imposed by the existing construction. Structural Engineers limited the number, size and spacing of penetrations through the floor slab, so that spigot velocities to the displacement terminals would be in excess of 5m/s (at maximum load), and this was not likely to be compatible with the room noise criteria of NR 35.

Our solution was to investigate the use of fabric Diffusers. The perceived advantages of a fabric diffuser were twofold. Firstly the large surface area would enable a proportionately large volume of air to be supplied without infringing on comfort criteria. Secondly the flexible nature of the fabric would lessen the regenerated air noise caused by the high spigot velocities. At that time, however, no measurement data was available to support this supposition of low noise.

To investigate noise and airflow performances, a fabric diffuser was designed (Figure 9) and manufactured for testing at Senior Colman's Test facility in Manchester. The tests excluded any architectural fascia, as it was felt that provided this could be constructed within certain defined criteria, notably a 50% minimum free area, airflow results would not be unduly compromised and the design would remain valid. The understanding at the time was that the fascia would be of vertical wooden slats.

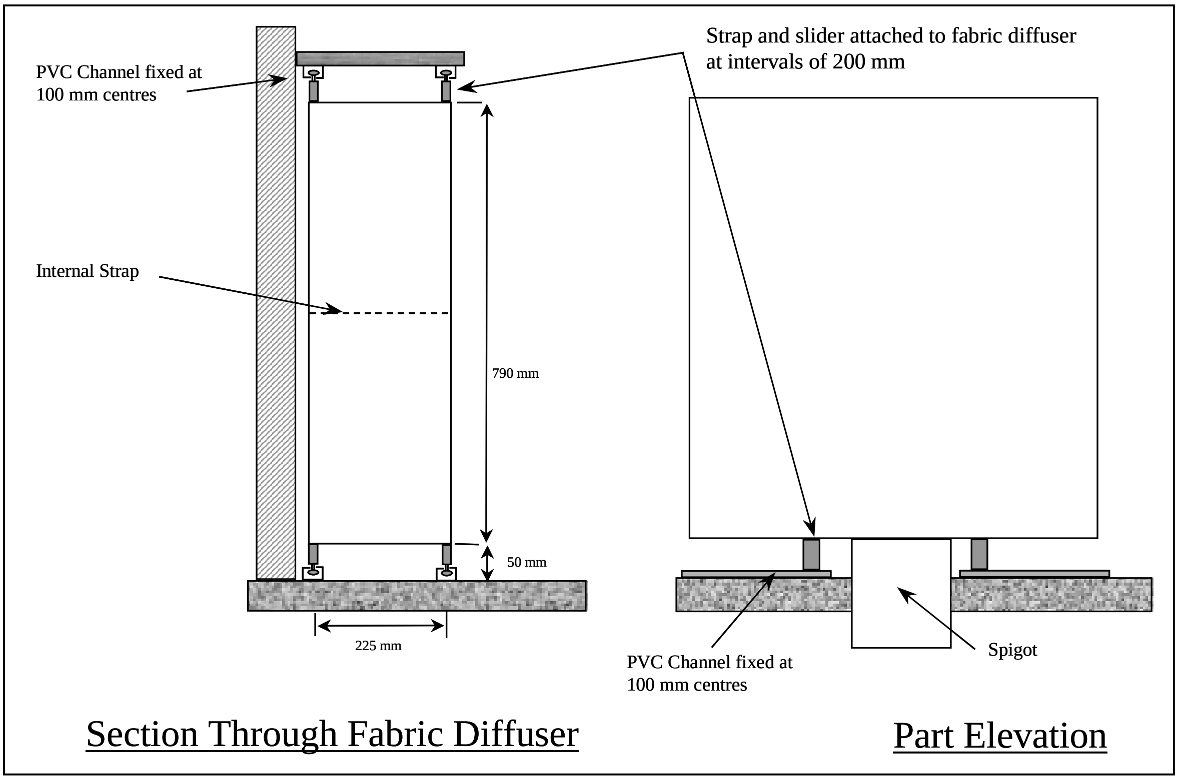


Figure No.9: –Fabric Diffuse

The acoustic tests highlighted the importance of the spigot connections where the provision of shoes provided a significant reduction in noise (6dBA). The internal straps within the diffuser were also relocated away from the spigot connections as these were found to vibrate in the airflow, and hence generated noise. The tests concluded that the room noise criteria could be achieved with a fabric face velocity of 0.2 m/s and spigot velocities of 4.2m/s some 20% below our initial design requirements.

<u>Installation and Commissioning</u>

The system within the restaurant operates on a VAV basis controlled against temperature or CO_2 as appropriate and measured in the exhaust air ducts. The system was commissioned in late 1998. Room criteria tests confirmed initial reports of localized 'cold drafts at low level'. A vertical velocity scan across the diffuser showed face velocities in the range of 0.4m/s to 0.67m/s averaging 0.58m/s higher than the design of value of 0.4m/s indicating some balancing problems. However the diffuser face velocities were also markedly directional with measurements showing a strong downward vector component. A dimensional check confirmed the architectural facia free area as 50% conforming to the specification.

This raised the question as to whether the increase in velocity through the architectural fascia was caused by incorrect commissioning or by the design of the facia. It was believed that the increased velocity and the downward vector of air movement was contributing to the low level drafts. A CFD model was constructed to investigate the air flows through the fascia.

A comparison of the airflow pattern with and without the architectural fascia was made based on the design parameters.

The results indicated that the profile of the fascia had a significant aerodynamic effects upon the airflow. The effect was to reduce the effective free area of the diffuser and hence increase the velocity (Figure 10). It could also be seen that the air velocities measured at floor level were increased as a result of the added momentum of the air at the fascia (Figure 11).

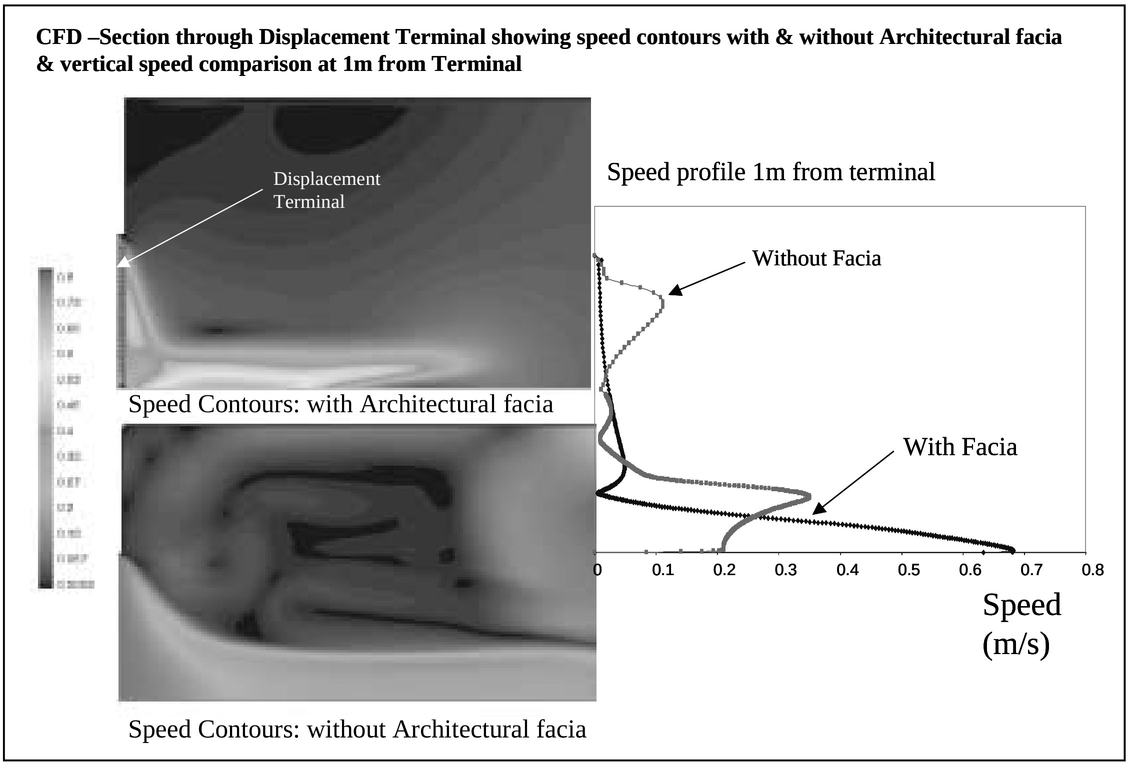


Figure No.10 –CFD Results-Impact of Architectural Fascia

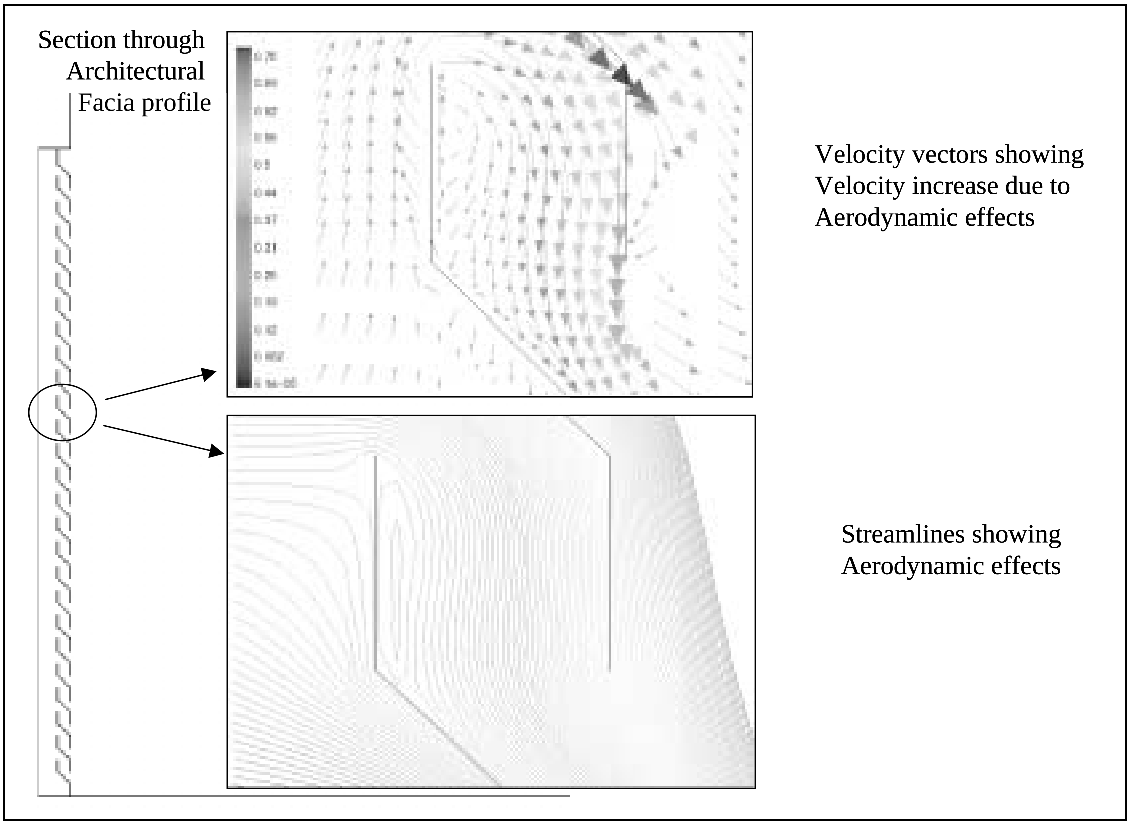


Figure No.11- CFD Detail of Aerodynamic Effects

The result of the added momentum was to exacerbate a problem inherent in the design. The architectural and structural restrictions had forced the designers to provide an active area of diffuser along an entire wall. All the air emanating from the diffuser effectively passes through a zone with a depth less than the height of the diffuser. The only way the velocity can decrease is to expand in the horizontal direction. Unfortunately this can not occur in this particular instance as the walls run for 5.5 m before an increase in width occurs.

Air Quality measurements carried out by Healthy Buildings International indicate that despite high levels of smoking all parameters remain below recommended levels. Initial CO_2 concentration measurements taken during periods of high occupancy have shown levels less than 650ppm at 1.8m AFFL. The controls have subsequently been adjusted to a higher setpoint.

Conclusion

Analysis indicated that Displacement Ventilation offers the designer a ventilation method that not only provides a high indoor air quality but can be engineered to operate with minimum energy consumption and CO_2 emissions. On-going IAQ monitoring has confirmed a high quality indoor climate despite periodic heavy smoking.

Whilst it was never envisaged that the system would operate at the ASHRAE 62 R @30 L/s/p fresh air design criteria, its adoption as a design standard created practical difficulties for the designers which were compounded by the restrictions of an existing construction and by the unforeseen influence of the architectural fascia on the Displacement outlets.

Whilst both the dilution mixing and the displacement systems were modelled to operate as efficiently as possible the inherent benefits of displacement design result in significant savings.

The use of a fabric diffuser enabled a high volume of air to be introduced into the space within the noise criteria set down in the brief. The architectural fascia had a significant and undesirable effect upon the airflow the result of which was to exacerbate the design shortcoming of the supply diffuser air flow being constrained between two flanking walls.

Whilst the peak flow draft problem remains unresolved the system actually operates well below the design maximum and hence low level air velocities are acceptable. This shows a further benefit of the Displacement Ventilation System coming from its superior ‘Ventilation Effectiveness’.

Anecdotally the restaurant is perceived as being ‘fresh’ and noticeably different from the office accommodation within the rest of the building which is conditioned by a combination of perimeter induction units and a conventional VAV system. The restaurant has no residual smoke odour nor is the odour perceptible during occupancy. Physical measurements confirm a high indoor air quality even with high levels of smoking.

Figures12 & 13 –Photographs

Despite the difficulties encountered from concept through to completion the displacement ventilation system has provided a healthy, invigorating indoor climate capable of operating with minimal environmental impact.

Acknowledgement:

The support of Dr. G. Whittle of Simulation Technology Ltd., Dr. Martin Gough of EDSL and John Middleton of Healthy Buildings International is gratefully acknowledged. Also to Andrew Geens, University of Glamorgan, for the inspiration in the use of fabric diffuers.

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[i] Fisk W.J., Rosenfeld A.H. 'Estimates of improved productivity and health from better indoor environments' -Indoor Air, No. 7, 1997 pp158-172

[ii] CIBSE ‘A’ Guide

[iii] BSR/ASHRAE Standard 62R-1989R- Ventilation for Acceptable Indoor Air Quality (August 1996) – Appendix E