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Summary A case study of the ventilation characteristics of office accommodation forming part of a recently refurbished building is presented. A mechanical system has been installed to ventilate and cool two floors that are interconnected by a series of atria, with a novel application of displacement ventilation applied where there is a very low ceiling height. The air distribution and air quality within the space have been studied by the application of computational fluid dynamics (CFD) to allow the computation of air change effectiveness in terms of local mean age. Variations in ventilation strategy have been explored and the results have been verified by perceived occupier satisfaction.

Air distribution and air quality in a large open space

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1 Introduction

It is often difficult to ensure that a ventilation system will provide good quality air throughout the whole of a large space. This is because the air distribution patterns are affected by the presence of obstructions and heat sources such as furniture, equipment and occupants. Recent studies[1,2] have shown that ventilation effectiveness parameters can be very useful both as a diagnostic tool and as a design aid in such cases. This paper reports on the application of ventilation effectiveness in both these roles to the provision of good quality air in a specific building. Three cases are considered. The first corresponds to the immediate post-handover period when the system operated in a manner configured by the occupants. The second refers to the system after it had been corrected to operate according to its intended design. The third is a proposed modification to the design for a future development.

2 The building and its ventilation system

The building, Boots D6, was constructed in the 1930s as part of the Boots Company headquarters at Beeston, Nottingham. The ground floor is used for manufacturing processes and the first floor for laboratories. The second and third floors are interconnected by a series of atria, and are now used to provide office accommodation. The building, of which an external view is shown in Figure 1, covers 200 m by 25 m in plan. It is constructed in reinforced concrete in the art deco style, as a result of which it has gained grade 1 listed status. For some years the upper floors of the building were surplus to Boots requirements, but now half of this architecturally important structure has been refurbished as the new headquarters office for Boots Healthcare International. A description of the refurbishment has been given by Parker[3].

The ventilation systems serving the second and third floors are designed using different principles. The second floor, with a 3.5 m floor-to-soffit clearance, is fitted with a 500 mm raised floor. The floor void acts as a pressurised plenum discharging air through swirl diffusers within the floor tiles. This allows the original 1930s concrete soffit (complete with imprints of the formwork) to remain exposed, a desire expressed by the client. Recirculation from the space is taken from just above head height (2.3 m) in front of the perimeter columns. Exhaust is allowed to rise through the atria to high-level grilles within the rooflights.

The third floor, by contrast, has a floor-to-soffit clearance of only 2.3 m. A pressurised floor was impractical (an 80 mm raised floor is installed for IT and power distribution) and a ceiling would not contain a useful void while retaining suitable head clearance beneath. The ventilation system adopted here is a displacement system, supplying air from (almost) continuous perimeter terminal units and at internal columns to a design fresh air supply rate of $12\ l\ s^{-1}$ per person. Air is discharged at a minimum of 4 degrees Celsius below room set point, at low velocity. The cool air flows across the floor, rising as it encounters heat gains. Recirculation at this level is from shallow plenums in the form of 100 mm deep bulkheads covering 5 m × 2 m of ceiling. These capture the rising (unwanted) warmed air from above personal computers and occupants, allowing cooler, fresher air to take its place. As with the second floor, air to be exhausted from the third floor is allowed to rise into the atria, from which it is extracted using the same fans as the air from the second floor.

Room temperature is measured using wall-mounted temperature sensors, which, via a Satchwell BAS 2000 Building Management System, control the off coil supply air temperature of the air handling unit.

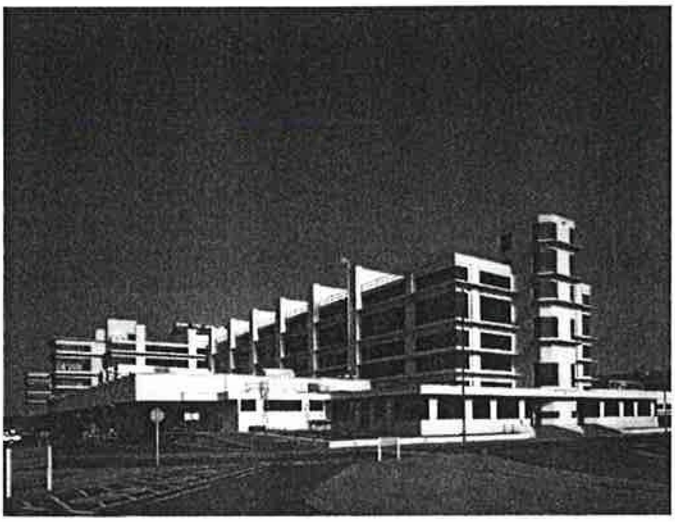

Figure 1 Boots D6 building. (Photograph © Martine Hamilton-Knight)

3 Post-handover observations

Once commissioned, the displacement air system serving the third floor performed well, with good temperature control and a high level of occupant satisfaction. However, although the second floor (floor plenum) system was performing satisfactorily during off-peak external conditions, it was failing to provide adequate comfort as the external conditions approached the design values. A number of occupants commented that their offices felt 'stuffy' and others felt that the internal temperature was too warm.

An on-site analysis that consisted of a series of occupant surveys was carried out by AMEC over a number of months. These resolved a number of local factors (e.g. draughts around external doors), but after these problems had been resolved approximately 50% of the occupants still complained of feeling stuffy and warm.

A number of temperature sensors were logged on the Building Management System (BMS) and these confirmed that internal temperatures were rising to between 1 and 2°C above the set point of 23°C, usually in the afternoons. The design team's initial thoughts were that air was leaking from the floor void, which would explain the poor temperature control and the stuffiness. The survey also revealed that the occupants had closed some of the floor diffusers, some had been moved to areas with low cooling load, and the total number of diffusers was less than in the original design. Reinstatement of the system to the original design configuration resulted in improvements to the occupant's perceived impressions of comfort, with occupant satisfaction level rising from approximately 50% to about 85–90%.

4 Air quality and the analysis of the ventilation system

Despite the improvement in occupant satisfaction, there remained some uncertainty about the true cause of the original complaints as the complaint level was greater than might have been expected for an excess temperature of no more than 2°C above set point. Clearly, the ventilation system must provide not only comfortable temperatures and temperature gradients, but also acceptable air velocities and satisfactory air quality. All of these depend not only on the overall rate of air supply but also on the distribution of the air within the space. However, the relationships between the air distribution pattern and each of these parameters are not necessarily the same. That is to say, a system that provides one of them may not provide the others. In particular, the provision of satisfactory temperatures and acceptable velocities does not guarantee satisfactory air quality. This is especially so in a large space, where the air quality at any point is the result of a complex mixing and distribution of fresh and stale air. It was clear that the original installation at Boots D6 was providing a sufficient supply of air and creating substantially correct temperatures and velocities. Nevertheless, there was a degree of user dissatisfaction. To investigate this it was decided to model all three parameters—temperature, velocity and fresh air distribution. The last of these can be characterised by one of the ventilation effectiveness parameters, such as the local mean age, the local air change index or the contaminant removal effectiveness. Definitions and descriptions of these may be found in the literature[4,5]. In this case, the principal contaminants are those due to the occupants, who are distributed approximately evenly over the floor area, and who move about in a manner typical of an open plan office environment. The principal contaminants therefore tend to be evenly supplied throughout the occupied zone, and so air quality is determined by the distribution of fresh air. In this circumstance, the most appropriate of the ventilation effectiveness parameters are the local mean age and the local air change index. The first of these was preferred, as it provides a measure of the quantity as well as the distribution of fresh air. The modelling process was therefore implemented to give the spatial distribution of temperature, air velocity and local mean age.

5 The modelling methodology

The temperature and air velocities throughout a ventilated space can be most satisfactorily achieved by means of computational fluid dynamics (CFD). The ventilation effectiveness parameters can be obtained within a CFD model, or by post-processing the CFD results. The latter technique is preferred here because it is more flexible and also, especially with a large model, uses significantly less computational time. The technique consists of extracting the intercellular flow rates from the CFD solution and then substituting them into the equation for local mean age:

$$\bar{\boldsymbol{\tau}} = \boldsymbol{F}^{-1}\boldsymbol{V}\boldsymbol{u}$$

where: $\bar{\boldsymbol{\tau}}$ = the vector of local mean age; $\boldsymbol{F}$ = the interzonal flow matrix; $\boldsymbol{V}$ = diagonal matrix containing zone volumes; $\boldsymbol{u} = -1$ vector.

The values of local mean age are then returned to the CFD software for the purpose of plotting contour diagrams. Full details of this process are described by Waters *et al.* [6].

The post-processing software does not at present take account of recirculated air, and hence the values of local mean age that are generated are with respect to an age of zero at the supply diffusers. This is equivalent to a full fresh air system with no recirculation. However, the Boots D6 building employs a fixed recirculation proportion of approximately 70%, which means that the supply air is a mixture of fresh air and air that is already old, with an age equal to its age at the point at which it is extracted. Furthermore, there are several extracts with different local mean ages. Because there is some uncertainty in the exact proportion of recirculation (and in any case this could alter according to damper settings), all the figures for local mean age have been plotted assuming full fresh air. Corrections to allow for recirculation are discussed separately.

6 The model

The commercially available CFD package 'Flovent' was used for this work with solutions based on the well-documented k-ε model. The finite-volume method used by Flovent requires the domain to be discretised into a series of cells, 247 632 for the model under consideration, and this, together with the fact that assumptions have to be made about boundary conditions for the specific case, means that the results should be considered as an indicative rather than an absolutely accurate portrayal of the internal environment.

In order to model the ventilation characteristics of the second and third floors of the building, a section between two consecutive grid lines was selected as being representative and this was modelled up to the centre line of symmetry, as shown in Figure 2. This section includes open plan office space at both levels 2 and 3 as well as the central atrium and the roof-light extract that provides ventilation exhaust from both floors. The design strategy for the space being modelled resulted in overall supply rates of 1.26 $m^3 s^{-1}$ and 1.06 $m^3 s^{-1}$

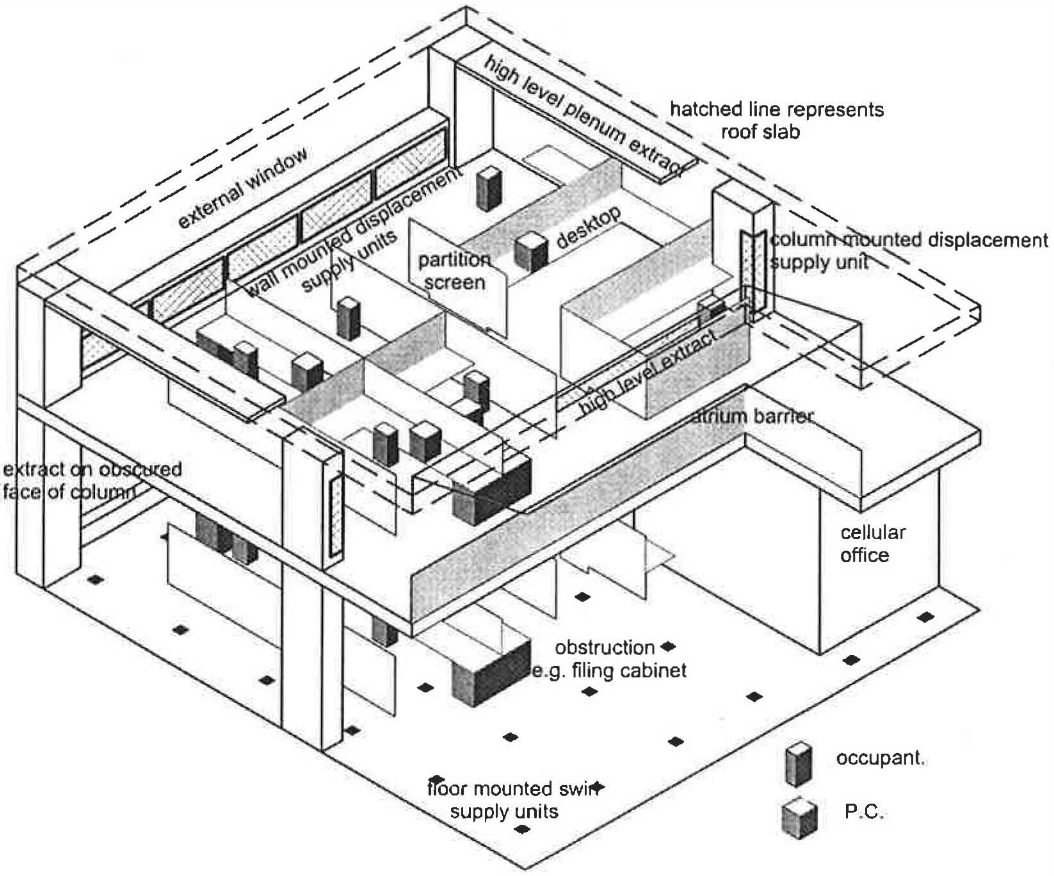

Figure 2 Isometric view of section of building modelled

to the second and third floors, respectively, making a total of 2.32 $m^3\,s^{-1}$. As the total volume is 717 m^3, this represents a nominal time constant of 5.2 minutes for the complete space. The air is supplied to the second floor from an underfloor plenum via circular 200 mm diameter floor-mounted swirl diffusers from which approximately 70% is extracted for recirculation at the external second-floor columns. On the third floor, of the air supplied from the displacement units located below the windows and within internal columns, approximately 70% is then withdrawn for recirculation by shallow high-level plenum extracts connected to ductwork in the external columns. The remainder of the supply air to both floors is combined to be exhausted at the atrium rooflight.

For the purposes of the model, an external ambient temperature of 27°C is assumed with supply air at 19°C from all outlets. The supply velocities from the third-floor wall and column diffusers were 0.25 and 0.17 $m\,s^{-1}$, respectively and the supply velocity at the second floor swirl units was 1.5 $m\,s^{-1}$, simulating commercially available units.

Smooth wall surfaces were assumed, these being modelled with respect to friction and heat transfer effects as defined in the Flovent instruction manual. The U-values of the external walls, windows and roof were set at 0.4, 5.7 and 1.6 $W\,m^{-2}\,K^{-1}$, respectively. Adiabatic conditions are assumed at the two grid lines and at the line of symmetry forming the limits of the section of the building being modelled. Convective heat flux was modelled for occupants, PCs and internal uplighters. Provision was made for the associated radiant flux at the internal surfaces.

7 Results

In modelling the effects on the system of the modifications made by the building's occupants, a number of alternative effects on air flow were explored. For the purposes of demonstration in this paper, it is assumed that increased pressurisation of the second-floor plenum due to closure and removal of more than half the floor diffusers resulted in an increased flow through the remaining units such that the overall flow reduction was only half the design flow through the missing units.

To examine fully the results for each case, it was found necessary to study vertical and horizontal sections on a series of planes. However, it is possible to illustrate the most significant features of each flow pattern by selecting representative sections. This has been done here by taking a horizontal section 1.6 m above the second floor level, and a vertical section A–A, the position of which is defined in Figure 5.

Case 1: Original installation, as configured by occupants

This case corresponds to the original installation as configured and operated by the building's occupants. Only 15 of the 32 supply diffusers in the second floor were operational, resulting in a different air distribution pattern from that which was intended. Nevertheless, the CFD solution for the temperature distribution, as shown in the vertical section in Figure 3, shows an acceptable result, with second-floor head-height temperatures between 21°C and 22°C and the substantially horizontal isotherms that are expected for a floor supply system. On the other hand, the results for local mean age for the same section (Figure 4) show a more vertical pattern with, in some areas of the second floor, high values at head height. In one particular spot at floor level, the lowest and highest values are to be found close together; this is an example of the effect of obstructions. The low values surround a working diffuser, whereas the high values are in a region shielded by an office partition that extends to floor level. The sudden transition occurs at the position of the partition. At a head height of 1.6 m, the horizontal section (Figure 5) shows substantial

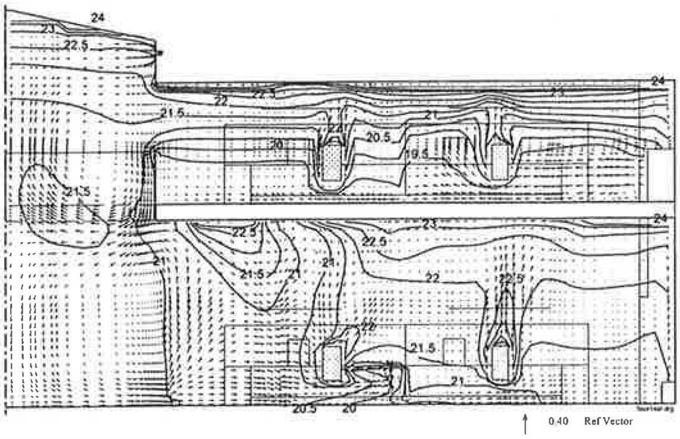

Figure 3 Isothermal contours (°C) and velocity vectors on plane A–A. As configured by occupants

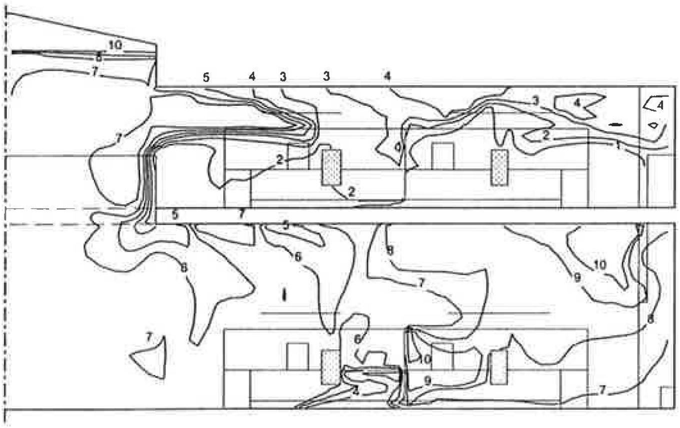

Figure 4 Local mean age contours (min) on plane A–A. Supply as configured by occupants

variations in local mean age, ranging from 4 to 10 minutes, instead of there being uniform low values; this is due at least in part to the reduced number of outlets and their irregular locations.

Case 2: Original installation, after correction to initial design

Case 2 corresponds to the installation as designed and currently operating, with all diffusers functioning. The temperature plots, of which Figure 6 is an example, were found to be satisfactory, being a slight improvement at second-floor level on the previous case, with a more even distribution up to head height, and a slightly lower temperature. There is a greater number of outlets and hence local mean age values are improved. However, the second-floor local mean age contours (Figure 7) still have a substantially vertical pattern. At head height there are considerable variations, again with high values in some areas. With air being introduced at floor level, the local mean age close to the floor would be expected to have low values. Figure 8, which is a horizontal section at 1.6 m above the second floor, shows that even at this height the low values are concentrated above the diffusers, with much higher values in between. The area of the floor that is protected by partitions has very high values. The implication is that the fresh air is being projected upwards in plumes rather than forming a horizontal displacement pattern. As expected, there is very little change to either the temperature or the local mean age contours over the unmodified floor 3.

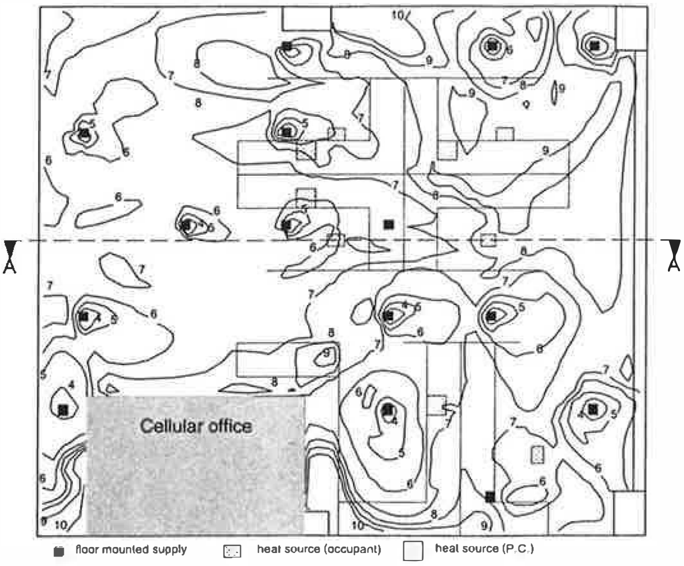

Figure 5 Local mean age contours (min) 1.6 m above lower floor level. As configured by occupants

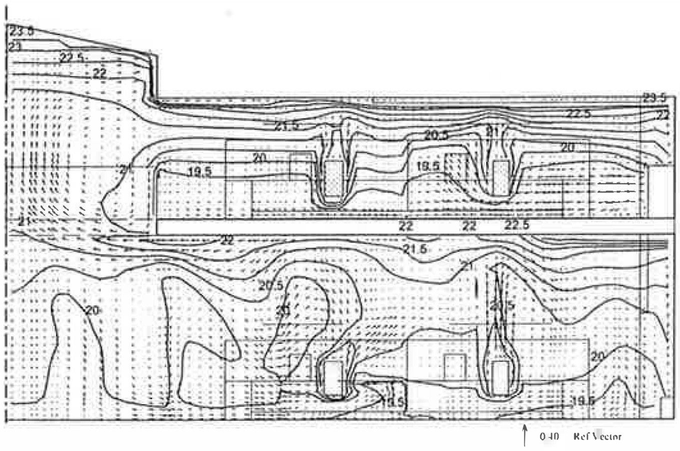

Figure 6 Isothermal contours (°C) and velocity vectors on plane A–A. Supply as initial design

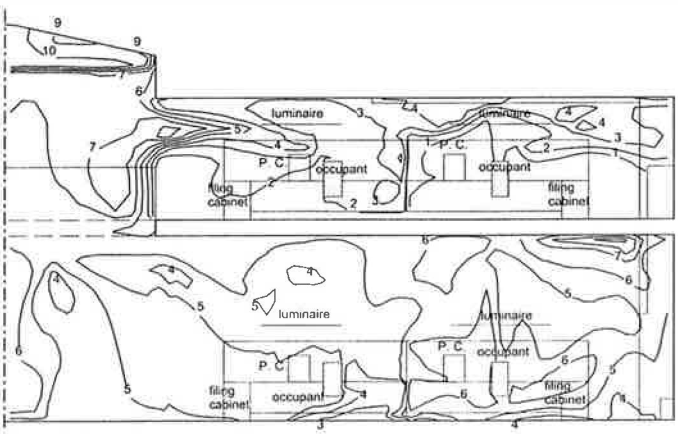

Figure 7 Local mean age contours (min) on plane A–A. Supply as initial design

Case 3: Proposed phase 2 design

Case 3 is a design proposal for the next stage of the building's rehabilitation. In this, two changes have been made from case 2. First, all partitions are designed to stand on legs with at least 700 mm clear space beneath them. Secondly, the second-

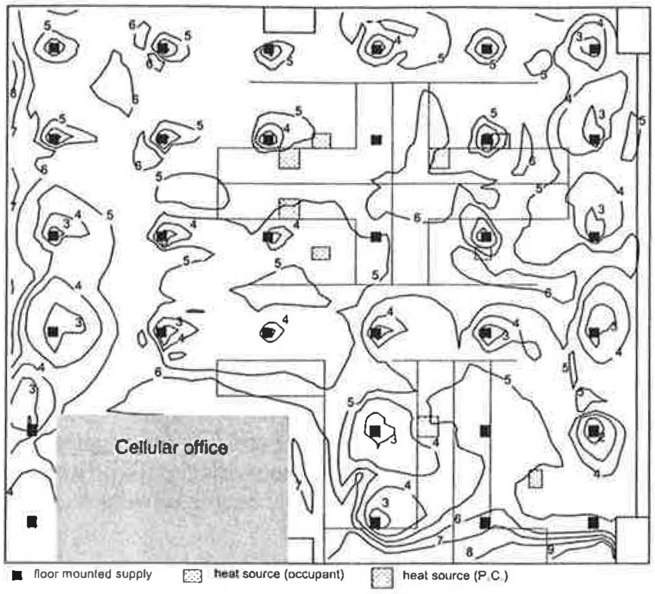

Figure 8 Local mean age contours (minutes) 1.6 m above lower floor level. Supply as initial design

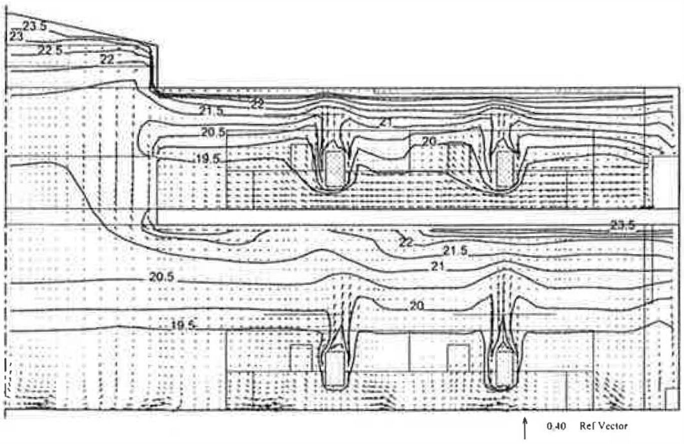

Figure 9 Isothermal contours (°C) and velocity vectors on plane A–A. Proposed phase 2 design

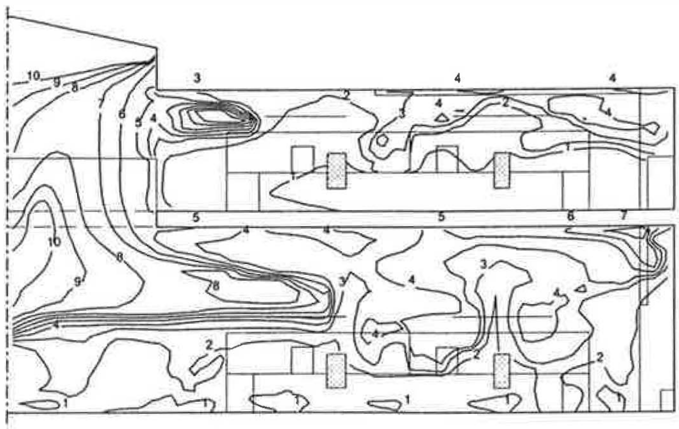

Figure 10 Local mean age contours (min) on plane A–A. Proposed phase 2 design

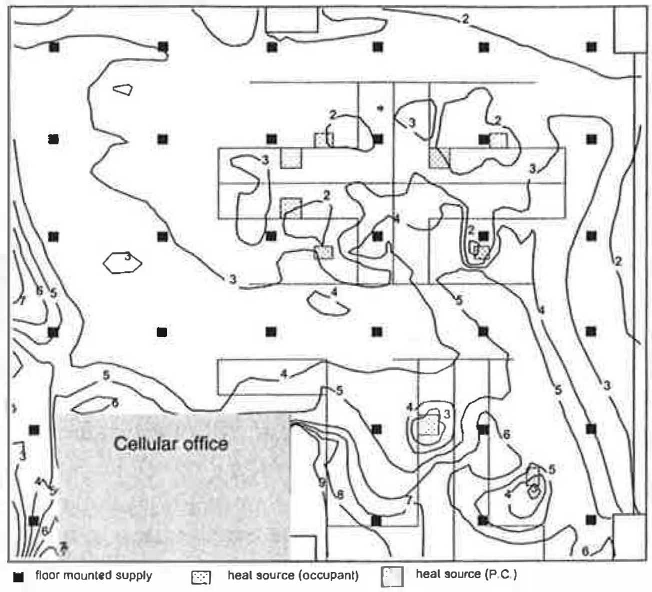

Figure 11 Local mean age contours (min) 1.6 m above floor level. Proposed phase 2 design

floor diffusers have a greater degree of swirl through increase of the angle of discharge from 20° to 60° to the vertical. In a previous study, Simons and Waters[7] found that a true displacement air distribution pattern would be produced when the vanes discharge the air at an angle of approximately 60° to the vertical. Figures 9 and 10 show that both the isotherms and the local mean age contours now have a horizontal pattern. The horizontal section (Figure 11) shows a uniform pattern of low values for the local mean age at both levels 2 and 3, and is a considerable improvement on case 2 (Figure 8). Furthermore, the raising of the partitions to allow clear space beneath them has enabled fresh air from the perimeter supply diffusers to penetrate along the floor to the full depth of the building. This is shown most clearly in Figure 12, in which the local mean age contours are plotted at a reduced interval of 0.2 min.

It is interesting to note that the air velocities close to floor level for this case are not significantly different from case 2. The difference is that in case 3 temperatures close to the floor are approximately 0.5°C less than case 2. It is unlikely that this will have any significant effect on the impression of draught.

8 Correction for recirculation

The local mean age contours in the sections and plans give a good indication of the distribution of air from the supply diffusers, but the values attached to the contours must be corrected for recirculation in the air handling unit. There is more than one method of doing this. On a small model, it would be possible to establish flow connections between the extract and inlet ducts, but the size of the model being considered here has led to the following correction procedure.

Let r be the fraction of exhaust air that is recirculated to the supply, and let τ_e be the local mean age at the exhaust when the supply is 100% fresh. If now the recirculation damper is suddenly opened, the air arriving at the supply diffuser will be a mixture with an average age of $r\tau_e + (1-r)0 = r\tau_e$. The zero occurs because the fresh air component has zero age. This raises the local mean age throughout the space, so that the age of the exhaust air is now $\tau_e + r\tau_e = (1+r)\tau_e$. On the next pass, the age at the supply is $r(1+r)\tau_e = (r+r^2)\tau_e$, and the age at exhaust is $\tau_e + (r+r^2)\tau_e = (1+r+r^2)\tau_e$. This gives rise to an infinite series:

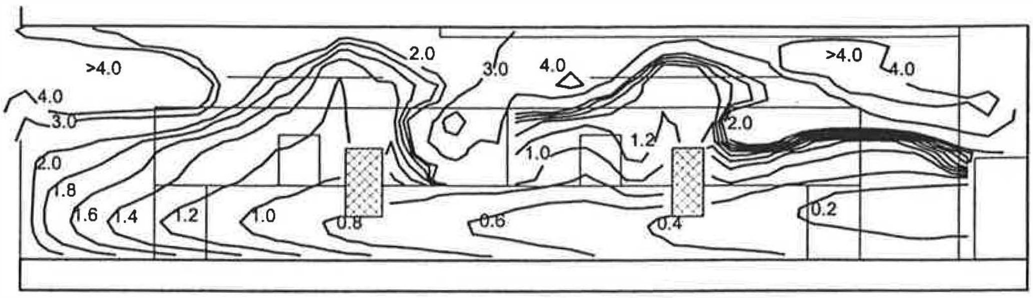

Figure 12 Local mean age (min), third-floor working zone on plane A–A. Proposed phase 2 design

	Age at supply	*Age at exhaust*
Full fresh air	0	τ_e
First pass	$r\tau_e$	$(1 + r)\tau_e$
Second pass	$(r + r^2)\tau_e$	$(1 + r + r^2)\tau_e$
*n*th pass	$(r + r^2 + \cdots + r^n)\tau_e$	$(1 + r + r^2 + \cdots + r^n)\tau_e$

These are standard geometric progressions, which when summed to infinity give

$$\text{Age at supply} = r\tau_e/(1 - r)$$
$$\text{Age at exhaust} = \tau_e/(1 - r)$$

In the Boots D6 building, recirculation is set at 70%, that is the recirculation factor $r = 0.7$. The results show that without recirculation the local mean age of the exhaust air varies between $\tau_e = 5$ min and $\tau_e = 7$ min, which means that in the steady state the age at the supply diffusers is in the range 12 to 16 min. Assuming the above argument to be valid, this must be added on to all the local mean age values obtained without recirculation. However, the amount to be added on is particularly sensitive to the true recirculation rate. For example, if this only slightly higher at 75%, the amount to be added would be between 16 and 21 min.

A more accurate method of calculating true local mean ages, by establishing flow connections between exhaust and inlet ducts, will be incorporated in future versions of the post-processing software.

9 Discussion and conclusions

The nominal time constant of 5.2 min corresponds to an overall air change rate of 11.5 air changes per hour. Assuming that the actual recirculation is indeed the intended 70%, the fresh air change rate is 3.5 air changes per hour. This would normally be expected to be satisfactory for the occupation density in this building. However, in case 1, there are areas of the occupied zone on floor 2 that, after adding the correction for recirculation, have local mean ages of about 25 min, which is equivalent to a local fresh air change rate of 2.4 air changes per hour. This again would not necessarily give rise to complaints. The difficulty with this analysis is that the recirculation is the difference between the total flow and the exhaust flow through the atrium rooflights, and it is quite possible that changes in temperature and wind pressure will cause this difference to fluctuate. For example, recalculating for an effective recirculation of 75%, the local fresh air change rate of 2.4 could fall to less than 2.0. When combined with the slightly elevated temperature and low local air velocities, this provides a plausible explanation for the complaints of stuffiness.

In case 2, the local mean age at head height is significantly lower than for case 1, as can be seen by comparing Figures 5 and 8. Apart from a small area near one perimeter, the highest value in Figure 8 is about 6 min, which becomes 21 min after allowing for 70% recirculation. The local fresh air change rate is therefore at least 2.9. This, together with the slightly better temperature control, appears to have been sufficient to overcome occupant dissatisfaction.

The results for cases 1 and 2 showed that partitions and office furniture have a significant effect on the local mean age, especially where the lower edge of the partitions is close to the floor. This is particularly important on the third floor, where, because the supply is mostly confined to the perimeter, the intended displacement flow is not fully established. In the proposed case 3 design, the absence of floor-level obstructions allows the supply air to travel across the floor, thereby achieving a much better displacement effect.

The overall conclusion is that the addition of a ventilation effectiveness parameter to the CFD evaluation process has enabled the design team to understand the dissatisfaction with the original (case 1) set-up, and the reasons for satisfaction with the improved (case 2) installation. These two cases showed little difference in internal temperature but large differences in local mean age. This is consistent with the findings on site, where the BMS log of temperature was respectable for case 1 but there were many reports of discomfort. This discomfort appears to have been due to the age of the air rather than its temperature. The local mean age predictions have also shown the effect of altering the diffuser characteristics, and the effect on displacement systems of floor-level obstructions.

References

1 Simons M W and Waters J R The effect on ventilation parameters of various ventilation strategies *Proc. 17th AIVC Conference, Gothenburg, Sweden* (September 1996)

2 Simons M W and Waters J R Local ventilation effectiveness parameters in air distribution system design *Building Serv. Eng. Res. Technol.* **19**(3) 135–140 (1998)

3 Parker A Boots made for working *Building Serv. J.* **19**(11) 30–32 (1997)

4 Sutcliffe H C *A guide to air change efficiency* AIVC Technical Report 28 (Coventry, UK: Air Infiltration and Ventilation Centre) (1990)

5 Brouns C E and Waters J R *A guide to contaminant removal effectiveness* AIVX Technical Report 28.2 (Coventry, UK: Air Infiltration and Ventilation Centre) (1991)

6 Waters J R, Simons M W and Leppard J The combined uses of CFD and zonal modelling techniques to aid the prediction and measurement of ventilation effectiveness parameters *Proc. 16th AIVC Conference, Implementing the Results of Ventilation Research, Palm Springs* (September 1995)

7 Simon M W and Waters J R Modelling supply devices in order to predict improvements in internal air quality *Proc. 19th AIVC Conference, Ventilation Technologies in Urban Areas, Oslo, Norway* (September 1998)