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Summary The ventilation effectiveness concept has been extensively used in research, where it has long been recognised as a good indicator of air quality. Also, there are many examples of its parameters having been measured as an aid to monitoring the air quality in completed buildings, usually to solve an air quality problem. However, despite their value as a predictor of the air quality to be achieved by an air distribution system, ventilation effectiveness parameters are rarely used in design. This paper shows that ventilation effectiveness parameters can easily be included in the design calculations, both early in simple modelling, and at a detailed advanced stage by association with a CFD model. The interpretation of the parameters is also explained.

Local ventilation effectiveness parameters in air distribution system design

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List of symbols

$c_i(t)$	Contaminant concentration in zone i at time t
$<c(\infty)>$	Steady-state contaminant concentration averaged over complete enclosure
q_i	Contaminant injection rate in zone i ($m^3 s^{-1}$)
ε^c or CRE	Contaminant removal effectiveness
ε_p or LACI	Local air change index at point p
ε_p^c or LAQI	Local air quality index at point p
$\overline{\tau_p}$	Local mean age of air at point p (s)
τ_n	Nominal time constant (s)
s_i	Total inflow/outflow to zone i ($m^3 s^{-1}$)
v_i	Volume of zone i (m^3)
f_{ij}	Volumetric flow from zone i to zone j ($m^3 s^{-1}$)
$\boldsymbol{C}(t)$	Contaminant concentration vector at time t
$\boldsymbol{F}$	Interzonal flow matrix ($m^3 s^{-1}$)
$\boldsymbol{q}$	Contaminant injection rate vector ($m^3 s^{-1}$)
$\boldsymbol{u}$	-1 vector
$\boldsymbol{V}$	Diagonal zonal volume matrix (m^3)
$\overline{\tau}$	Local mean age vector (s)

1 Introduction

The distribution of fresh and contaminated air in ventilated spaces is rarely completely uniform. In general, therefore, air quality will vary throughout a space, and it is the designer's task to ensure that air quality in the occupied zone is good. The two most common strategies for producing a design solution are mixing ventilation and displacement ventilation. Mixing ventilation attempts to achieve good air quality by providing a total ventilation rate high enough to ensure that the quality is everywhere the same, thereby making it a simple matter to calculate the minimum proportion of fresh air within the total. This however is inefficient, as the ventilation system will be providing good air quality in parts of the space where it is not needed, as well as expending a large amount of energy on creating the necessary mixing. Displacement ventilation achieves good air quality by introducing fresh air within the occupied zone, usually (but not necessarily) at low level, and allowing contaminated air to be swept into unoccupied parts of the space. This is considered to be more efficient than a mixing strategy because only the occupied zone is maintained at a high level of air quality, and energy is not wasted on unnecessary stirring.

Whichever approach is adopted, it is difficult for a designer to predict, for a proposed system, the air quality distribution in a space. Engineering parameters such as the throw constants of a diffuser, or the expected velocity vectors, while useful, are not measures of air quality, and can only be related to it by inference. On the other hand the local values of some of the ventilation effectiveness parameters are direct measures of air quality at a point within a space, and are therefore a much better indication of the likely success or otherwise of a proposed design. Despite their potential value in the design process, ventilation effectiveness parameters appear to have been used much more as a diagnostic measuring tool to commission or 'troubleshoot' an existing system. Sateri et al. have reported typical examples of this, as have Waters and Brouns(1,2). Nevertheless techniques for the use of ventilation effectiveness parameters in design have been reported by, for example, Fang and Persily and by Haghighat *et al.*(3,4). In particular, Liddament(5) has reviewed the rôle of ventilation effectiveness in design.

The purpose of this paper is to demonstrate how ventilation effectiveness parameters may be used at the design stage, and to report a particular methodology linked to a computational fluid dynamics (CFD) model. First the relevant parameters are introduced and defined; this is necessary because there is no universal agreement on naming conventions. Application of the parameters is then demonstrated for a simple case. The procedure for a complex case involving CFD is then described, and then applied to a particular example.

2 Ventilation effectiveness parameters

The most commonly used measures of ventilation, air change rate and its reciprocal the nominal time constant τ_n, share the disadvantage of relating to the whole space and not reflecting the variability of air movement within the space. This may be overcome by the ventilation effectiveness concept, due originally to Sandberg(6), the parameters of which fall into two distinct categories. These are *air change efficiency*, which is a measure of how effectively the fresh air provided by the ventilation system is distributed throughout the room, and *contami-*

nant removal effectiveness, which is a measure of how well a contaminant is removed from a point in the room. A comprehensive description and discussion of all these parameters is given in References 7 and 8 respectively. The parameters of relevance to this paper are as follows.

2.1 Air change efficiency

The *local mean age* of air is defined as the average time it takes for air to travel from the inlet to any point p in the room, and may be written as:

$$\bar{\tau}_p = \int_0^\infty t A_p(t) \mathrm{d}t \tag{1}$$

where $A_p(t)$ represents the age distribution curve for air arriving at point p. The local mean age of the air is different for all points p within the room. Although it is questionable to do so, the reciprocal of the local mean age is sometimes interpreted as the local air change rate.

The *local air change index* LACI or ε_p characterises the age of air at a point relative to the overall supply rate and is defined as:

$$\mathrm{LACI} = \varepsilon_p = \tau_\mathrm{n}/\bar{\tau}_p \tag{2}$$

As the LACI is a ratio with the nominal time constant, values greater than one indicate that the point is receiving air more efficiently than a perfect mixing system, and *vice versa*. These indices provide information about the distribution of fresh air. From the definition of local mean age it will be apparent that the lower its value at a point, the better the supply of fresh air to that point. On the other hand, the larger the LACI at a point, the better the distribution of fresh air to that point.

2.2 Contaminant removal effectiveness

The *local air quality index* LAQI or $\varepsilon_p^{\,c}$ is defined as the ratio between the steady-state concentration of contaminant at the exhaust duct and the steady-state concentration of contaminant at a point p in the room:

$$\mathrm{LAQI} = \varepsilon_p^{\,c} = c_\mathrm{e}(\infty)/c_p(\infty) \tag{3}$$

The set of values of LAQI for all points in a room depends on the distribution and strength of the contaminant sources. Since contaminant may be injected anywhere within a room, there is a different set of values of LAQI for each possible distribution of contaminant sources.

The *contaminant removal effectiveness* CRE or ε_c is defined as the ratio between the steady-state concentration of contaminant in the exhaust air and the steady-state concentration averaged over the whole of the room:

$$\mathrm{CRE} = \varepsilon^\mathrm{c} = c_\mathrm{e}(\infty)/\langle c(\infty)\rangle \tag{4}$$

This index gives an average performance for the whole room, but its value also depends on the location of the contaminant source. There is therefore a unique single value of the contaminant removal effectiveness for each possible distribution of contaminant sources. The computation of contaminant removal effectiveness indices is most appropriate when local or general release of non-occupant pollutants is anticipated. Large values of either of these indices are an indication that the pollutant is being removed efficiently.

Note that if there is more than one exhaust duct, $c_\mathrm{e}(\infty)$ is the concentration that would exist if all the exhaust air were fully mixed.

5 Design procedure for a simple case

In many cases, probable air quality can be estimated by a combination of elementary calculations and reasonable assumptions. For example, Figure 1 is a cross section through a naturally ventilated factory building. This case may be treated by a two-zone model. For a particular wind and temperature regime, wind pressure and stack effect calculations (for which the simple methods recommended by CIBSE(9) are often adequate) provide estimates of the flows through the windows and roof ventilators. Also, from a knowledge of activities within the factory, an assumption can be made for the rate of internal air movement between the upper and lower zones. The resulting flow rates are shown in the figure, and can be used to assess the effectiveness of the ventilation by computing:

(*a*) the nominal time constant τ_n and the air change rate

(*b*) the local mean age of air τ_p and the local air change index ε_p

(*c*) the local air quality index $\varepsilon_p^{\,c}$.

The additional formulae required to find the necessary parameters are given by Sandberg(10):

$$\bar{\tau} = \boldsymbol{F}^{-1}\boldsymbol{V}\boldsymbol{u} \tag{5}$$

$$\boldsymbol{C}(\infty) = \boldsymbol{F}^{-1}\boldsymbol{q} \tag{6}$$

where

$$\boldsymbol{u} = \begin{bmatrix} -1 \\ -1 \\ \cdots \\ -1 \end{bmatrix} \qquad \boldsymbol{q} = \begin{bmatrix} -q_1 \\ -q_2 \\ \cdots \\ -q_n \end{bmatrix}$$

$$\boldsymbol{F} = \begin{bmatrix} -s_1 & f_{21} & \cdots & f_{n1} \\ f_{12} & -s_2 & & \\ \cdots & & \cdots & \\ f_{1n} & & & -s_n \end{bmatrix}$$

$$\boldsymbol{V} = \begin{bmatrix} v_1 & & & \\ & v_2 & & \\ & & \cdots & \\ & & & v_n \end{bmatrix}$$

The inverse matrix $\boldsymbol{F}^{-1}$ can be derived and equations 5 and 6 evaluated quite easily on many portable calculators, or by means of suitable mathematics software such as Matlab(11).

Firstly, from Figure 1, the total inflow/outflow of the whole building so is $0.54\,\mathrm{m^3\,s^{-1}}$, and the total volume is $1400\ \mathrm{m^3}$. The

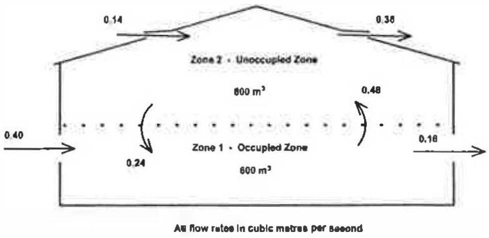


Figure 1 Cross section of factory unit

nominal time constant is thus $n = 1400/0.54 = 2593$ s, or 43 minutes. This time constant corresponds to an air change rate of $60/43 = 1.4$ air changes per hour.

Secondly, Figure 1 also shows that the total inflows/outflows to the inner zones are $s_1 = 0.64 \mathrm{m^3 s^{-1}}$ and $s_2 = 0.62 \mathrm{m^3 s^{-1}}$. The flow matrix $\boldsymbol{F}$ and its inverse $\boldsymbol{F}^{-1}$ are therefore

$$\boldsymbol{F} = \begin{bmatrix} -0.64 & 0.24 \\ 0.48 & -0.62 \end{bmatrix}$$

$$\boldsymbol{F}^{-1} = \begin{bmatrix} -2.2017 & -0.8523 \\ -1.7045 & -2.2727 \end{bmatrix}$$

and the volume matrix is:

$$\boldsymbol{V} = \begin{bmatrix} 600 & 0 \\ 0 & 800 \end{bmatrix}$$

Direct substitution in equations 5 and 2 gives, for the occupied zone (zone 1), local mean age $\tau_1 = 2003$ s or 33.4 minutes; local air change index $\varepsilon_1 = 1.29$. For the unoccupied zone (zone 2), local mean age $\tau_2 = 2841$ s or 47.4 minutes; local air change index $\varepsilon_2 = 0.91$.

Thirdly, by applying equations 6 and 3, the local air quality index may be found. In this case, there are three possibilities:

(*a*) contaminant released in zone 1 only

(*b*) contaminant released in zone 2 only

(*c*) contaminant released uniformly throughout the whole building (i.e. in proportion to the volume of each zone).

The contaminant injection matrix $\boldsymbol{q}$ for each of these cases is:

Case (*a*):

$$\boldsymbol{q} = \begin{bmatrix} -1 \\ 0 \end{bmatrix}$$

Case (*b*):

$$\boldsymbol{q} = \begin{bmatrix} 0 \\ -1 \end{bmatrix}$$

Case (*c*):

$$\boldsymbol{q} = \begin{bmatrix} -0.6 \\ -0.8 \end{bmatrix}$$

Note that in case (*c*), it is unnecessary to make the components of $\boldsymbol{q}$ sum to unity; it is only their relative values that matter.

The results are given in Table 1.

Table 1 Local air quality indices for two-zone model

Location of contaminant release	LAQI	
	ε_1^c, Zone 1	ε_2^c, Zone 2
Zone 1	0.84	1.09
Zone 2	2.17	0.81
Zones 1 and 2	1.29	0.91

4 Interpretation of results

The overall fresh air ventilation rate of 1.4 air changes per hour is likely to be sufficient to provide satisfactory air quality in this type of building. Furthermore, the fresh air supply to the occupied zone is better than the overall ventilation rate suggests, because the local mean air age in this zone is less than the nominal time constant; that is, the local air change index ε_1 is significantly greater than 1. The good distribution of fresh air may also be noted by calculating the local fresh air ventilation rate, which may be found by multiplying the overall rate by ε_1 (1.4×1.29) to give 1.8 air changes per hour.

The implications of the results for contaminant removal are more complex. When contaminant is released in the occupied zone only, the local air quality index of that zone is less than 1, suggesting that contaminant is being removed inefficiently. This is because the ventilation system is also removing uncontaminated air from the unoccupied zone. However, when contaminant is released in zone 2, or uniformly throughout the space, ε_1^c is greater than 1, showing that in these cases the system is removing contaminant from the occupied zone efficiently.

A useful feature of the application of ventilation effectiveness parameters to a simple zonal model is that different scenarios can be tested very quickly. For example, it may be useful to consider the effect if the 0.38 $\mathrm{m^3 s^{-1}}$ outflow from the roof ventilator were reduced to, say 0.2 $\mathrm{m^3 s^{-1}}$ by closing it slightly, whilst maintaining the same overall ventilation rate. The outflow through the window would have to increase from 0.16 to 0.34 $\mathrm{m^3 s^{-1}}$, and the internal flows would change, with, say, the flow from zone 1 to zone 2 increasing from 0.24 to 0.42 $\mathrm{m^3 s^{-1}}$. The flow matrix and its inverse become:

$$\boldsymbol{F} = \begin{bmatrix} -0.82 & 0.42 \\ 0.48 & -0.62 \end{bmatrix}$$

$$\boldsymbol{F}^{-1} = \begin{bmatrix} -2.0209 & -1.3690 \\ -1.5645 & -2.6728 \end{bmatrix}$$

All other matrices are the same, and the results become as follows. For the occupied zone (zone 1) the local mean age $\tau_1 = 2308$ s or 38.5 min; the local air change index $\varepsilon_1 = 1.12$. For the unoccupied zone (zone 2) the local mean age $\tau_2 = 3077$ s or 51.3 min; the local air change index $\varepsilon_2 = 0.84$.

Table 2 Revised local air quality indices for two-zone model

Location of contaminant release	LAQI	
	ε_1^c, Zone 1	ε_2^c, Zone 2
Zone 1	0.92	1.18
Zone 2	1.35	0.69
Zones 1 and 2	1.12	0.84

These results show that the local air quality index in the occupied zone has improved from 0.84 to 0.92 for the case when contaminant is released in it, but has worsened for the other two cases. If it is expected that contaminant will be released in the occupied zone only, the new ventilation pattern is better than the first.

5 Design procedure for detailed analysis of complex cases

The procedure described in sections 3 and 4 may be refined to give more detailed design information by increasing the number of zones. However, as the number of zones increases, it becomes more difficult to use simple methods to establish the inter-zone flows which are required for the flow matrix $\boldsymbol{F}$. This difficulty may be overcome by using a computational fluid dynamics (CFD) model. Such a model may be used to predict the distribution of a contaminant in the space, and then to obtain the required ventilation effectiveness parameter from the contaminant distribution. This approach can be time consuming, as it may be necessary to run the CFD model several times in order to obtain all the relevant parameters. This can be avoided by the approach adopted here, which is to undertake an initial analysis of the internal space using CFD in order to establish velocity vectors and intercellular flow rates. These flow rates are then post-processed by entering them into the $\boldsymbol{F}$ matrix in software developed at Coventry University for the computation of the required ventilation effectiveness parameters. The current version of the post processing software has been written to be compatible with the 'Flovent' CFD model(12), and the computed ventilation effectiveness parameters can be returned to 'Flovent' for presentation. An additional advantage of this approach is that the post-processing software can include extra facilities for analysis.

In order to demonstrate the type of information that may be obtained from the prediction of ventilation effectiveness parameters, an analysis has been performed and results obtained for the building shown in Figure 2. The results of this case study have been expressed in terms of local air change index, an appropriate parameter if it is required to assess the efficiency of the ventilation system rather than study the removal of pollutants. The indices have been expressed as contour diagrams since this allows very rapid evaluation of the spatial adequacy of the ventilation provided. The building is representative of the type of modern structure that could be used for engineering manufacture in a location where extremes of temperature could be expected. The building was selected to closely resemble a Finnish factory unit which has been used as a case study for the International Energy Agency Annex 26 Project *Energy efficient ventilation of large enclosures*(13).

The model is of a factory building 40 × 30 m in plan and 8 m high with wall, roof and window thermal transmittances of 0.45, 0.25 and 2.8 $\mathrm{Wm^{-2}K^{-1}}$ respectively. Miscellaneous heat sources are present within the building which, as indicated in Figure 2, is equipped with both mixing and displacement ventilation systems.

Operation of the ventilation systems has been modelled assuming the environmental conditions described below.

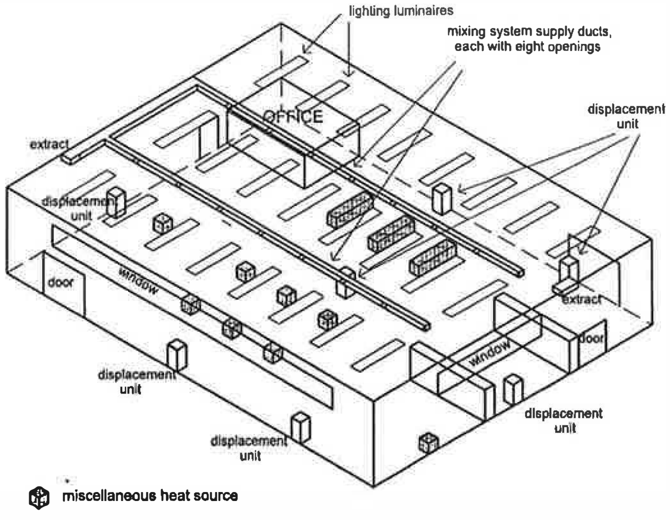


Figure 2 Factory with mixing and displacement ventilation systems

For the mixing ventilation system an ambient temperature of 5°C is assumed. Air is supplied through 16 roof-mounted duct openings, each supplying 0.44 kg $\mathrm{s^{-1}}$ (0.37$\mathrm{m^3s^{-1}}$) at 18°C. This gives an overall air change rate of 2 per hour and corresponds to winter heating in the UK.

For the displacement ventilation system an ambient temperature of 24°C is assumed. Air is supplied through 7 floor-mounted displacement flow diffusers at a velocity of 0.3 m $\mathrm{s^{-1}}$ and a temperature of 16°C. The data used for the performance of the diffusers are typical of those for current products. This gives an overall air change rate of 2.2 per hour, and corresponds to a low-level, low-turbulence displacement supply suitable for providing summer cooling in the UK.

6 Consideration of results

6.1 Mixing ventilation system

Velocity vectors and temperature contour lines at the level of the working zone are shown in Figure 3. As can be seen from the figure, the air velocity appears satisfactory and the temperature across the majority of the space ranges from 18.5 to 19°C, the contour lines of higher values corresponding to positions directly above the heat sources.

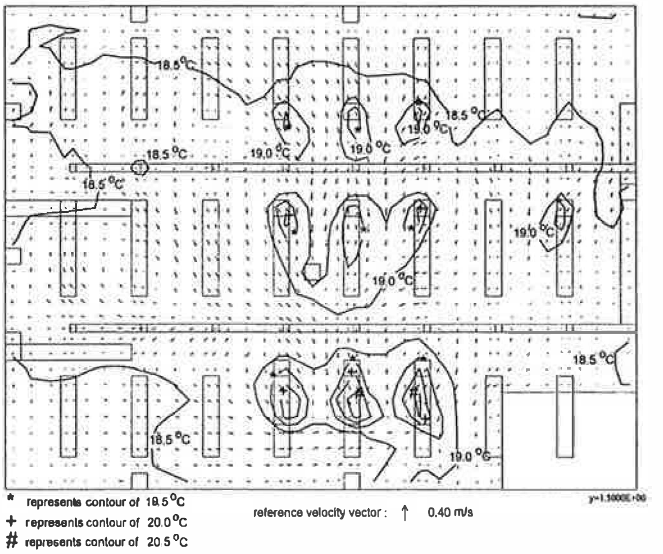
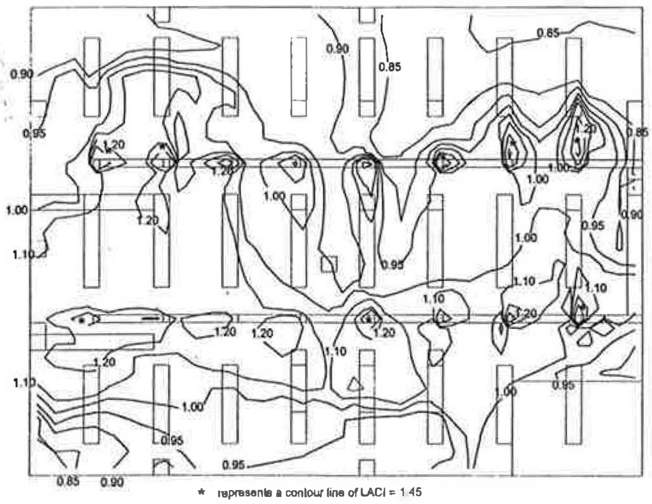


Figure 3 Mixing ventilation velocity vectors and temperature 1.5 m above floor level

Figure 4, which corresponds to the same plane as Figure 3, displays values of LACI ranging from less than 0.85 to greater than 1.2. Since an LACI of 1 represents perfect mixing and values less than 1 correspond to worse than average ventilation, it is possible to identify large areas of poorly ventilated space within the working zone. It will be seen that these correspond to areas with low rates of air movement.

Variability of LACI in the vertical plane is shown in Figure 5. LACI values on the plane remote from the air supply outlets are considerably lower than those on the plane in its vicinity. It is interesting to note, however, that at high level the LACI drops to 0.95 in close proximity to the outlets. The characteristics of the ventilation close to the supply outlets, from which the direction of air flow is normal, is shown more clearly in Figure 6. This demonstrates that although, as expected, there



* represents a contour line of LACI = 1.45

Figure 4 Mixing ventilation LACI contours on plane 1.5 m above floor level

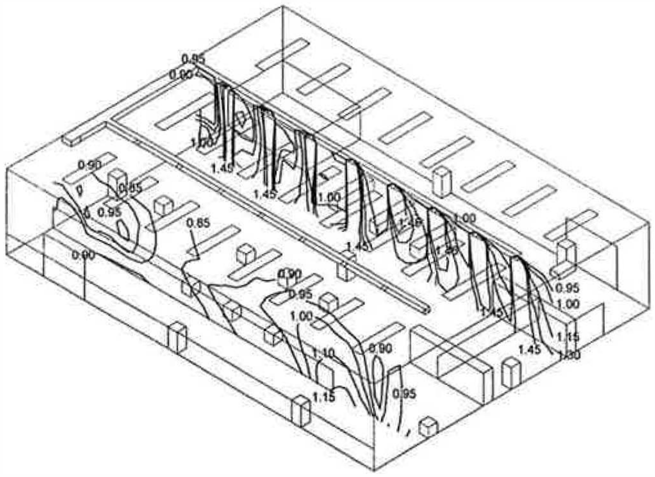


Figure 5 Mixing ventilation contour diagrams of laci on vertical planes

are very high values of the index immediately below the outlets, within 2 m horizontally from the supply, its value drops to values of approximately 1 over the full height of the building. This is indicative of good mixing and indeed it may be concluded that over most of the space the mixing system is working satisfactorily. This example demonstrates how LACI provides a useful indicator of ventilation effectiveness.

6.2 Displacement ventilation system

The distribution of the LACI resulting from operation of the displacement system, assuming summer conditions in northern Europe, is shown for horizontal planes at various heights in Figures 7–9. A displacement system working perfectly would result in values of LACI considerably greater than one at floor level, reducing with height, assuming ceiling-mounted extracts, to values well below one at ceiling level as cool air trickling into the enclosure at low level is gradually displaced upwards.

The results clearly show that there are large values of the index 0.5 m above floor level, and also that it tends to decrease with height. They also show, however, considerable variation on each plane with large values of the index extending to high levels as shown in Table 3.

Table 3 Range of LACI at various heights

Height(m)	Range of LACI	
	from less than	to greater than
0.5	1.3	1.9
2.5	0.8	1.3
5.5	0.7	1.3

However, it should be noted that the plan area over which the index is high, i.e. greater than one does, as expected, reduce with height.

Apparent anomalies in the LACI associated with the displacement system can be explained by the vertical contours shown in Figure 10. There are, as anticipated, a series of approximately horizontal LACI contour lines, the values of which reduce with height, but superimposed upon them are upward 'plumes' of high LACI, the locations of which correspond to the spaces above the heat sources. This suggests that the displacement system is working correctly but that it is being modified by the circulatory convection of air heated by local heat sources.

7 Conclusions

It has been shown that computation of ventilation effectiveness parameters is a valuable part of the evaluation of an air distribution system. These parameters give a direct assessment of the indoor air quality due to both the distribution of fresh air and the removal of contaminated air. The use of the *local air change index* is of particular value for evaluating the distribution of fresh air in large open enclosures in which

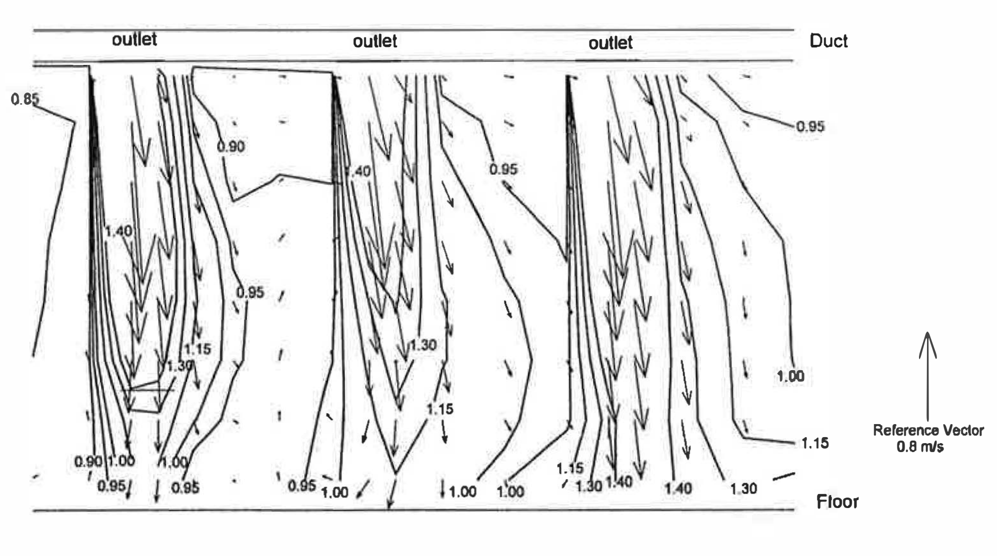


Figure 6 LACI contours and velocity vectors in vicinity of mixing system outlets

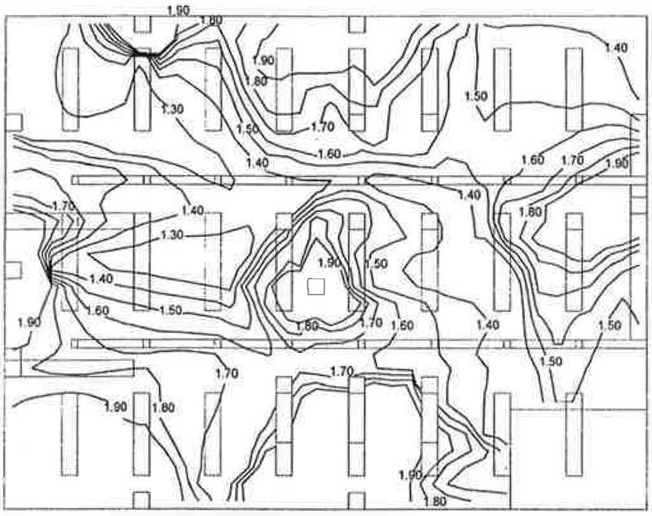


Figure 7 Displacement ventilation LACI contours on plane 0.5 m above floor level

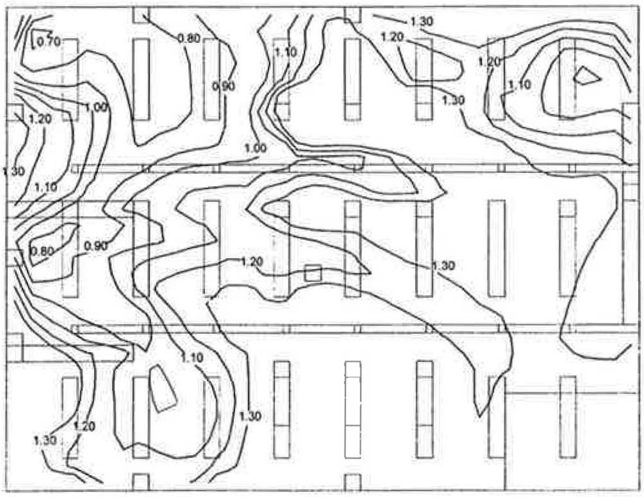


Figure 8 Displacement ventilation LACI contours on plane 2.5 m above floor level

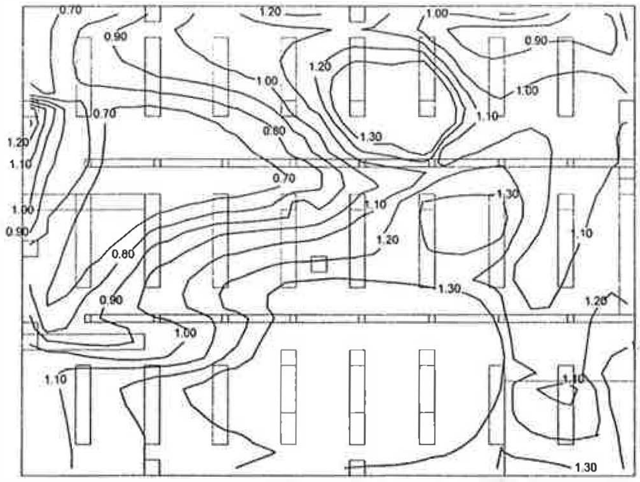


Figure 9 Displacement ventilation LACI contours on plane 5.5 m above floor level

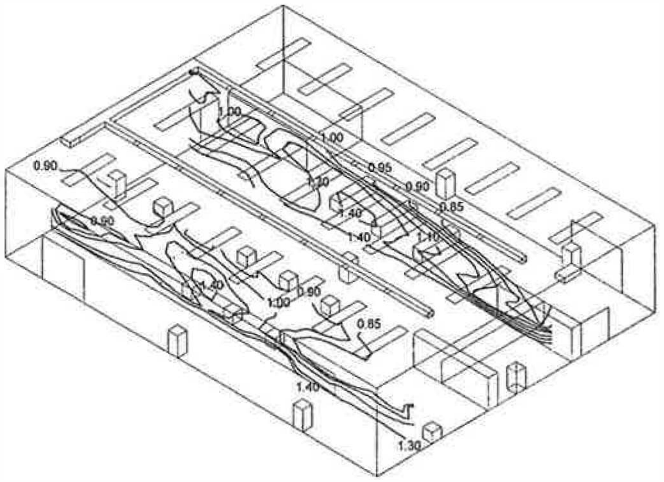


Figure 10 Displacement ventilation contour diagrams of LACI on vertical planes

large variations in air quality are likely to exist, and where it is required to assess the effect of localised features such as obstructions or heat sources. The case study results suggest that such analysis may be of value even in the case of relatively simple buildings since the air distribution patterns, particularly with displacement ventilation in operation, are often more complex than anticipated. The *local air quality index* is valuable in assessing situations where internal process cause the release of offensive or toxic pollutants. In such cases the LAQI may be more useful than LACI in providing an indication of probable air quality.

It has also been shown that the ventilation effectiveness parameters can be obtained from simple zonal models, and can therefore be used early in the design process. As a design progresses, more detailed predictions can be obtained from CFD analysis.

References

1 Sateri J O, Seppanen O A and Majanen A T Ventilation effectiveness in residential buildings with various ventilation systems *ASHRAE Trans.* 97(2) 1102–1111 (1991)

2 Waters J R and Brouns C E Measurement of ventilation effectiveness parameters in an electronics factory *Proc. 13th AIVC Conf. Ventilation for Energy Efficiency and Optimum Indoor Air Quality, Nice, France* pp269–283 (Sept 1992)

3 Fang T and Persily A Numerical prediction of airflow patterns and ventilation effectiveness in an open office environment *Proc. 12th AIVC Conf. Air Movement and Ventilation Control within Buildings, Ottawa, Canada* vol. 3 pp181–182 (Sept 1991)

4 Haghighat F, Zheng Jiang and Wang J A CFD analysis of ventilation effectiveness in a partitioned room *Indoor Air* (4) 606–615 (1991)

5 Liddament M The role application of ventilation effectiveness in design *Proc. ISRACVE, Tokyo* pp59–72 (July 1992)

6 Sandberg M What is ventilation efficiency? *Building and Environment* 16(2) 123–135 (1981)

7 Sutcliffe H C *A Guide to Air Change Efficiency* AIVC Technical Report 28 (Coventry, UK: Air Infiltration and Ventilation Centre) (1990)

8 Brouns C E and Waters J R *A Guide to Contaminant Removal Effectiveness* AIVC Technical Report **28.2** (Coventry, UK: Air Infiltration and Ventilation Centre) (1991)

9 *CIBSE Guide* Section A4 (London: Chartered Institution of Building Services Engineers) (1986)

10 Sandberg M The multi-chamber theory reconsidered from the viewpoint of air quality studies *Building and Environment* **19**(4) 221–233 (1984)

11 MATLAB software (South Natick, MA 01760, USA: The Mathworks Inc) (1989)

12 FLOVENT software version1.4 (Hampton Court, UK: Flomerics Ltd)

13 Niemela R, Koskela H and Hautalampi T *Ventilation and Indoor Climate in a Manufacturing Plant* Report **42** (Helsinki: Finnish Institute of Occupational Health) (1995)