Air Distribution in Rooms, (ROOMVENT 2000)
Editor: H.B. Awbi

13355

THE EFFECT OF RECIRCULATION ON VENTILATION EFFECTIVENESS PARAMETERS

J R Waters and M W Simons

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

ABSTRACT

The effect on ventilation effectiveness parameters of the recirculation of air is investigated. The results of work with respect to air change effectiveness parameters is explained and extended to the effect of recirculation on the contaminant removal effectiveness parameter of local air quality index. It is demonstrated, first with respect to a simple system with one supply and exhaust and then by extension to a system with multiple exhausts, that it is possible to calculate the effect of recirculation by means of a simple algebraic expression. It is explained how the procedure for the computation of ventilation effectiveness parameters by the multi-zonal method may be adapted to include the effects of recirculation.

KEYWORDS

air quality, contaminant removal effectiveness, local air quality index, local mean age, recirculation, zonal model

INTRODUCTION

When calculating values of the ventilation effectiveness parameters for a room, it is often assumed that the air entering at the supply diffusers is wholly fresh. Whilst this is sometimes true, especially for natural ventilation, mechanical systems often recirculate a high proportion of the exhaust air. The supply air is therefore a mixture of fresh and recirculated air, and so values of the ventilation effectiveness parameters calculated on the basis of full fresh air are not correct. In the particular case of local mean age, the problem was solved in a simplified way by Waters *et. al.* (2000) in a case study of a large open plan office building. The general solution for local mean age with recirculation has been given by Waters and Simons (2000). This paper extends the theory to local air quality index and contaminant removal effectiveness, and considers the implications for indoor air quality.

THE SIMPLE CASE

Consider the most basic ventilation system with a recirculation loop as shown in Figure 1, with a total air flow rate through the room of Q. Let r be the fraction

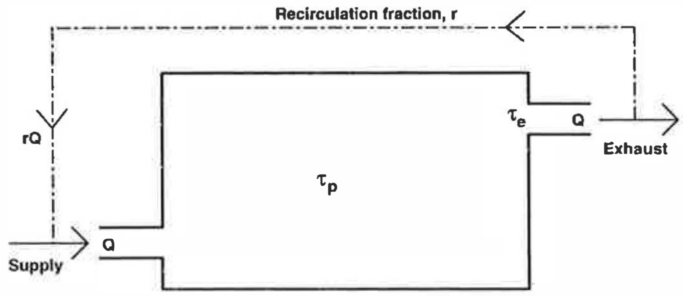

Figure 1: Simple system with recirculation

of exhaust air which is recirculated to the supply, and let τ_e be the local mean age at the exhaust when the supply is 100% fresh. It has been shown (Waters and Simons, 2000 and Waters *et. al.*, 2000) that for any point, p, within the space whose local mean age without recirculation is $\tau_p^{(r=0)}$, the corrected local mean age in the presence of recirculation is given by Eqn. 1.

$$\text{Local Mean Age at point p} = \tau_p = \tau_p^{(r=0)} + \frac{r\tau_e}{1-r} \tag{1}$$

where τ_p is the local mean age at point p with recirculation. Thus a simple add-on term allows for the effect of recirculation on local mean age.

Unfortunately it is not possible to use a simple add-on term to allow for the effect of recirculation on the Local Air Quality Index (LAQI). This is because an add-on term is applied to the contaminant concentration field to which the LAQI is *inversely* proportional. In the simple case of figure 1, the exhaust concentration is $\frac{q}{(1-r)Q}$, where q is the total contaminant release rate in the room. The concentration of the inlet air may now be considered as a mixture consisting of rQ parts at a concentration of $\frac{q}{(1-r)Q}$, and (1-r)Q parts at zero concentration. The inlet concentration is thus $\frac{rq}{(1-r)Q}$, and the effect of recirculation will be to raise concentration levels at any point p within the room by this amount, as shown in Eqn. 2,

$$c_p = c_p^{(r=0)} + \frac{rq}{(1-r)Q} \tag{2}$$

where c_p and $c_p^{(r=0)}$ are, respectively, the concentrations at point p with and without recirculation. The local air quality index which is defined (Brouns and Waters, 1991) at point p as

$$\text{LACI} = \varepsilon_p^c = \frac{c_e(\infty)}{c_p(\infty)} \tag{3}$$

may then be calculated from

$$\varepsilon_p^c = c_e^{(r=0)} c_p^{-1} \tag{4}$$

Note that the LAQI is defined in terms of the exhaust concentration in the absence of recirculation. This is because, as the recirculation fraction increases, the contaminant concentration at all points within the room approaches the exhaust concentration, and so the LAQI approaches unity everywhere. This would be meaningless. Also, by using $c_e^{(r=0)}$, a comparison between the recirculation and non-recirculation cases may be made. It is still the case that as recirculation is increased, LAQI approaches uniformity, but its numerical value will now be reduced, indicating the deleterious effect of recirculation on air quality.

EXTENSION TO MULTIPLE EXHAUSTS

In practice, most systems have multiple supply diffusers and extracts. If the recirculated air passes through a single central air handling unit, then all the supply diffusers receive and deliver air of identical quality, and so the correction to the local mean age is the same as for the single diffuser case described above. However, in the case of multiple extracts, the air leaving each extract will in general have differing local mean ages and exhaust concentrations. Also, depending on the ductwork layout and the duct pressure distribution, the exhaust flows and recirculation fractions may differ. This is shown in Figure 2, which illustrates the point with three exhaust ducts. The total air flow rate through the space is again Q. The outflows at the exhausts are Q_1 , Q_2 , Q_3 with recirculation proportions r_1 , r_2 , r_3 . The local mean ages and concentrations at the exhausts in the absence of recirculation are τ_{e1} , τ_{e2} , τ_{e3} , and c_{e1} , c_{e2} , c_{e3} .

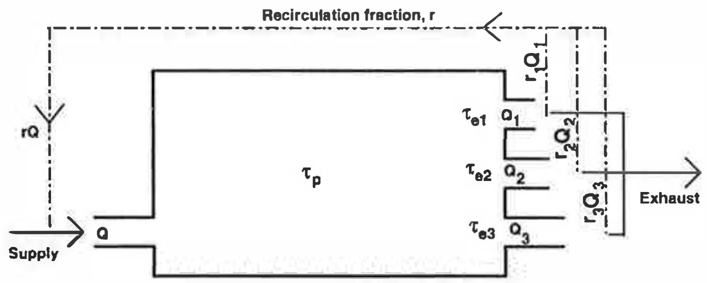

Figure 2: System with multiple exhausts

The local mean age with recirculation is now given by Eqn. 4 (see reference 2).

$$\text{Local Mean Age at point p} = \tau_p + \frac{1}{(1-r)Q}\sum_{i=1}^{3} r_i Q_i \tau_{ei} \tag{5}$$

with the summation being taken over all exhausts. In order to calculate LAQI, it is easily shown that Eqn. 2 must be replaced by Eqn. 6, with Eqn. 4 unchanged.

$$c_p = c_p^{(r=0)} + \frac{1}{Q}\Sigma r_i Q_i c_{ei} \tag{6}$$

THE GENERAL CASE

The above methods are convenient for simple cases. The general case can be treated by means of the multi zonal model. As an example, consider the room shown in Figure 3, which has two supply diffusers and three extracts, and is divided into 12 zones. Local values of the ventilation effectiveness

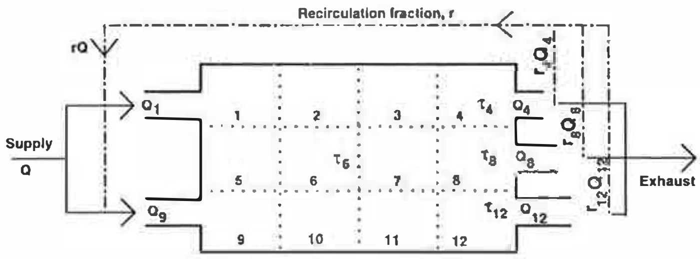

Figure 3: Zonal system with twin supplies and multiple exhausts

parameters are found for each of the discrete points p into which the volume s divided from the flow matrix, **F**, the volume matrix, **V**, the -1 vector, $\underline{u}$, and the contaminant release vector, $\underline{q}$. defined as follows.

$$\mathbf{F}=\begin{bmatrix} -s_1 & f_{1,2} & f_{1,3} & \cdots & f_{1,n} \\ f_{2,1} & -s_2 & f_{2,3} & \cdots & f_{2,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ f_{n,1} & f_{n,2} & f_{n,3} & \cdots & -s_n \end{bmatrix}$$

where f_{ij} = the flow to i from j.

$$\mathbf{V}=\begin{bmatrix} v_1 & 0 & \cdots & 0 \\ 0 & v_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & v_n \end{bmatrix} \qquad \underline{u}=\begin{bmatrix} -1 \\ -1 \\ \vdots \\ -1 \end{bmatrix} \qquad \underline{q}=\begin{bmatrix} -q_1 \\ -q_2 \\ \vdots \\ -q_n \end{bmatrix}$$

where v_i and q_i are the volume and contaminant release rate for zone i. The local mean age is found from Eqn. 7 (Sandberg, 1984), and the contaminant concentration from Eqn. 8 (Brouns and Waters, 1991).

$$\underline{\tau} = \mathbf{F}^{-1}\,\mathbf{V}\,\underline{u} \qquad (7)$$

$$\underline{c} = \mathbf{F}^{-1}\,\underline{q} \qquad (8)$$

where $\underline{\tau}$ is the vector of local mean ages and $\underline{c}$ is the vector of concentrations. In this case the LAQI is calculated from:

$$\underline{\varepsilon}^{c} = c_e^{r=0}\,\underline{d} \qquad (9)$$

where $d_i = 1/c_i$

Note that the flows to and from the outside air (denoted as the zero zone) do not appear in the flow matrix, and that the s_i entries on the diagonal are the sums of the total flows into and out of each zone.

Flow rates to and from the external air are implied by the algebraic sum of each s_i and the flows in its corresponding row or column. Row sums give supply rates and column sums give exhaust rates. The effect of the recirculation loop, therefore, is to alter only the entries for flows connecting exhaust zones to supply zones. The corresponding alterations to supply and exhaust are taken care of by the row and column sums. Referring to the room in Figure 3, and assuming that the recirculated air is divided equally between the two supplies, the flow matrix is given by Eqn. 9 (Waters and Simons, 2000).

$$\mathbf{F}=\begin{bmatrix} -s_1 & f_{1,2} & f_{1,3} & f_{1,4}+\frac{1}{2}r_4Q_4 & \cdots & f_{1,8}+\frac{1}{2}r_8Q_8 & \cdots & f_{1,12}+\frac{1}{2}r_{12}Q_{12} \\ f_{2,1} & -s_2 & f_{2,3} & f_{2,4} & \cdots & f_{2,8} & \cdots & f_{2,12} \\ f_{3,1} & f_{3,2} & -s_3 & f_{3,4} & \cdots & f_{3,8} & \cdots & f_{3,12} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ f_{9,1} & f_{9,2} & f_{9,3} & f_{9,4}+\frac{1}{2}r_4Q_4 & \cdots & f_{9,8}+\frac{1}{2}r_8Q_8 & \cdots & f_{9,12}+\frac{1}{2}r_{12}Q_{12} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ f_{12,1} & f_{12,2} & f_{12,3} & f_{12,4} & \cdots & f_{12,8} & \cdots & -s_{12} \end{bmatrix} \quad (10)$$

The inverse of this matrix may then be used in Eqns. 7 and 8 to find the desired parameters. Clearly Figure 3 and its flow matrix can be generalised.

DISCUSSION

The significance of the recirculation factor, r, on ventilation effectiveness parameters may be demonstrated by way of a simple example. Assume that an enclosure has single supply and extract points, that the air within is completely mixed and that the local mean age at the extract and at point p is 2 minutes. The effect of recirculation which is shown in Figure 4 is self explanatory, a value of r =0.5 doubles the local men age and high values of r result in very high ages.

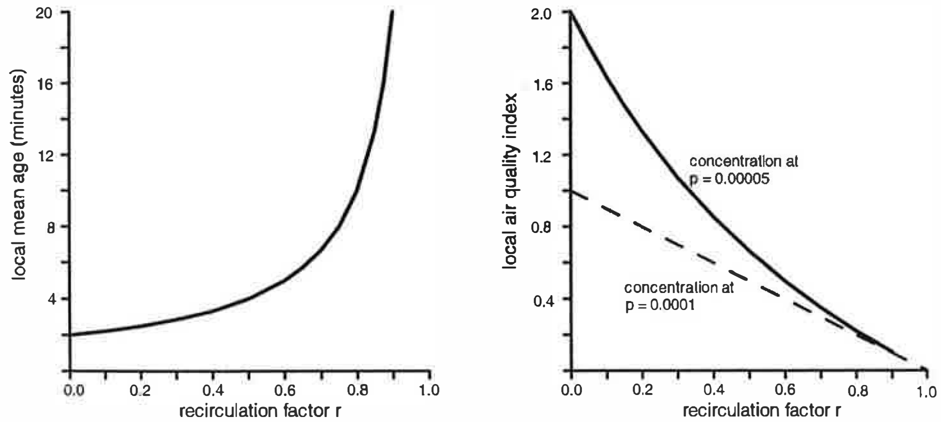

Figure 4: The Effect of Recirculation on Local Mean Age and Local Air Quality Index

The effect of recirculation on the contaminant removal effectiveness of a system is equally important. Assume that contaminant is released into the fully mixed system referred to above and that the resultant concentrations , without recirculation, are:

$$c_e = c_p = 10^{-4}$$

The result of the recirculation factor on LAQI is demonstrated by the straight line relationship shown in figure 4, i.e. the LAQI of 1 which is associated with completely mixed air and no recirculation, reduces in a linear manner towards zero. The consequence if perfect mixing did not exist and point p was relatively well ventilated with a steady state concentration, in the absence of recirculation of $0.5 * 10^{-4}$ is also shown in Figure 4. From a value of LAQI = 2 without recirculation this index falls rapidly at low values of r toward zero as r approaches 1.

It may be concluded that the effects of recirculation on ventilation effectiveness parameters is very significant and that it should not be ignored when assessing air quality..

REFERENCES

Waters J.R. Simons M.W, and Grazebrook J. (2000). Air Distribution and Air Quality in a Large Open Space. To be published, *Building Services Engineering Research & Technology.*

Waters J.R. Simons M.W. (2000). Local Mean Age in Ventilation Systems with Recirculation. To be published, *Building Services Engineering Research & Technology.*

Sandberg M. (1984). The multi-chamber theory reconsidered from the view-point of air quality studies. *Building and Environment*, **19(4),** 221-233.

Brouns C. and Waters J.R. (1991). *A Guide to Contaminant removal Effectiveness.* Air Infiltration and Ventilation Centre, Coventry, UK