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Summary The tracer gas method is one of the most widely used methods for measuring flow rates for building air infiltration and ventilation. The accuracy of this method depends vitally on the spatial uniformity of the tracer/air mixing. However, information on this critical problem has been scarce, largely due to the practical difficulty in experimentally obtaining data. In the last decade a new tool for building research has emerged, namely computational fluid dynamics or CFD. A study of tracer/air mixing has been carried out using a time dependent CFD method, supported by conceptual/dimensional analysis. In this study, 12 cases of tracer/air mixing in simulated tracer decay tests were computed. Each case had a different zonal volume or other boundary or initial conditions. By comparing these results, it was found that there were many factors affecting tracer/air mixing and, contrary to a previous report, there does not exist a universal critical value of air change rate below which satisfactory mixing is guaranteed, although lower air change rates are generally beneficial to mixing. In addition, it has been demonstrated that smaller building zones and higher inlet air flow velocities have positive effects on tracer/air mixing while the initial tracer concentration level has no effect. Finally a statistical parameter of concentration spread coefficient for assessing tracer mixing has been introduced.

Tracer gas mixing with air

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List of symbols

A	Area of a surface across which tracer diffusion occurs (m^2)
C	Tracer concentration (% by volume)
C_0	Initial tracer concentration (% by volume)
C_{max}	Maximum value of tracer concentration in a zone (% by volume)
C_{min}	Minimum value of tracer concentration in a zone (% by volume)
$\bar{C}$	Mean tracer concentration as defined by equation 2 (% by volume)
D	Binary diffusivity ($m^2 s^{-1}$)
F	Rate of tracer diffusion ($m^3 s^{-1}$)
g_C	Tracer concentration gradient ($\% m^{-1}$)
k	Coefficient of tracer concentration variation (%)
m	The amount of tracer diffused (m^3)
N	Number of sampling points in a building zone (Non-dimensional)
P_{EK}	Turbulence kinetic energy production per unit mass ($m^2 s^{-3}$)
R	Equivalent radius of the air jet (m)
s	Coefficient of the spread of tracer concentration (%)
U	Mean (as opposed to 'turbulent') velocity ($m s^{-1}$)
$\langle u_i u_j \rangle$	Representing Reynolds stresses ($m^2 s^{-2}$)
V	Zone volume (m^3)
α	Factor of zonal dimension increase
1, 2	Denoting the zones used in Group 1 and 2 (in equations 8, 9, 10)

1 Introduction

Tracer techniques are now very important methods for quantifying building air infiltration and ventilation. They have been applied to single zone and multi-zone buildings[1], to pressure driven and temperature-driven (stack effect) air flows[2], to small residential buildings and large commercial/industrial buildings[3]. They have also been used simultaneously with fan pressurisation techniques to measure building leakage distributions[4, 5]. It is envisaged that the techniques will be used increasingly in the future, as their accuracy and effectiveness improve.

Despite their ever wider application, there is a persistent potential problem related to all versions of the tracer gas technique, including the concentration decay method, constant concentration method, constant injection method and pulse injection method. That is the discrepancy between the less than perfect tracer mixing achieved in practical tests and the theoretical requirement of all the above methods that the tracer concentration in the zone under test be uniform at any moment within the duration of the test. This requirement implies that supply air entering the zone must instantly achieve uniform mixing with the air and tracer mixture in the zone. This is physically unsound. Despite having a weak theoretical basis, the tracer gas techniques have been quite successful. The reason is that in many cases the tracer concentration can be made fairly uniform and so the measured flow rate, being insensitive to small non-uniformity, gives an adequately accurate indication of the true flow rate. Although the tracer concentration distribution is the ultimate measure of the tracer mixing uniformity, there have been other measures of assessment. For example, in the case of applying the tracer decay method to a single zone, reasonable uniformity is indicated by the tracer concentration decay curve reasonably coinciding with an exponential curve. Similar 'coincidence' phenomena exist for multi-zone applications[6]. In fact such 'coincidence' checks should be made before each new application to ensure the flow rate measurement accuracy. In cases of poor tracer mixing, i.e., tracer concentration being far from uniform, some form of artificial enhancement of mixing is required. The most popular method for this purpose is the use of an oscillating fan. This simple technique has proven to be very effective for this purpose. However, some researchers believe that the mixing fan introduces a new problem, i.e. disturbing the flow rates to be measured. This problem is particularly acute in the measurement of natural air infiltration, the driving force of which is weak in relation to that of the fan flow. Although some alleviation of this problem can be effected by properly positioning the fan so that its flow does not directly impinge on the inlet or outlet of the flow being measured, the fact that many flows being measured are with unknown inlet or outlet positions makes even the alleviation of the problem difficult. As a result, the use of a mixing fan for tracer mixing enhancement is confined to a limited number of situations.

The above discussion shows that tracer/air mixing is still, in general, an unsolved problem for all versions of the important tracer gas techniques. It is probably the single most serious problem which pevents the tracer gas technique from becoming a routine, day-to-day test method that can be effectively used by every building services practitioner. However, despite the importance of the issue, there has not been much research of this problem. One of the few published works in this area is that of Alevantis and Hayward(3) who studied the effect of air change rate on the tracer concentration distributions. They concluded that there is a critical value in the air exchange rate, $0.5\,\mathrm{ac\,h^{-1}}$, above which mixing is poor and below which mixing is good. By mixing being poor or good, it is meant that the coefficient of concentration variation is respectively larger or smaller than 10%. Both the conclusion and the definition will be examined later in this paper. The reason for the lack of information on the issue lies in the practical difficulties in the relevant experimental investigations. To study tracer concentration distribution, tracer concentration at many points must be measured simultaneously many times. As in multi-zone tracer gas tests, to establish the tracer concentration distribution, many parallel tracer analysing systems are required and as they are expensive, they are used only by a limited number of research institutions.

In the last few years a new tool has emerged for building engineering research, namely computational fluid dynamics or CFD. Although it has not been used as widely in the building services industry as in some other industries, notably the aerospace industry, nevertheless it has been successfully applied to the modelling of building pressure (wind induced) coefficients(7), air and airborne pollutant/moisture movement within buildings(8) and building thermal performance(9). The CFD technique provides valuable insights into processes for which experimental investigations are difficult to perform, as in the case of tracer gas techniques. However, it should be said that, because it is not yet fault-proof, CFD results should be treated as indicative clues rather than definitive conclusions and, whenever possible, should be substantiated with results from other sources. In this study, simple conceptual/dimensional analyses were performed in addition to the CFD computations. The effects of the following parameters on the tracer/air mixing were examined: the air change rate, the volume of the building zone, the initial tracer concentration and the velocity of the infiltrating air stream. It was felt that, contrary to the claim of Alevantis and Hayward(3), the air change rate is not the only parameter affecting tracer/air mixing. Among the many versions of the tracer gas method, the tracer concentration decay technique is the most widely used and the following examination will focus on this technique. It is felt, however, that the results thereby obtained are also applicable to other versions of the tracer gas method, although it is highly desirable that they be confirmed with separate computations.

2 Calculation procedures

In this work, the CFD code FLUENT was used, which solves the three dimensional Navier–Stokes equations, i.e. the momentum equations, the continuity equation and the mass transfer (for the tracer gas) equation. To simulate the transient tracer concentration decay, the time dependent versions of the above equations were used.

2.1 Turbulence model

To deal with turbulent flows, FLUENT solves the averaged Navier–Stokes equations, with additional Reynolds stress terms. These unknown stresses were modelled, in this case, using the standard k–ε model, which links these terms, via two equations to other flow parameters. This model has been used extensively with good accuracy to simulate building air flow in zones of simple geometries such as those in this study.

2.2 Computation domain, boundary and initial conditions

The zones or rooms used in this study, or the calculation domain, are of cubic shape. Flow modelling using just one shape geometry enables the study to concentrate on the effects of other factors described in Section 1. Examination of the effect of building/zone geometry is beyond the scope of this study, mainly due to the large number of building zone shapes available. The three-dimensional computation domain is selected in preference to the two-dimensional one, despite the penalty in CPU processing time. It is felt that in a two-dimensional domain, the stream from the inlet to the outlet will divide the domain into separate areas, isolating them from each other, resulting in mixing being artificially obstructed. Such a situation does not occur in reality. Therefore, two-dimensional simulation of mixing processes should be avoided.

There is a wide range of tracer species(10). In theory any gas that can be detected at low concentrations can be used as a tracer. Suitable candidates include the non-toxic helium, nitrogen and carbon dioxide and the less healthy freons, nitrous oxide and sulphur hexafluoride (SF_6). The former however are less susceptible to detection and therefore higher initial concentrations will have to be used in a tracer decay test. Because of the wide range of possible tracers and the initial conditions, it is not possible to examine each of the possibilities. So in this study, one tracer gas with a molecular weight of 28, a diffusivity of $0.2\,\mathrm{cm^2\,s^{-1}}$ and, except for one case, an initial concentration of 0.1% was used. The gas happened to be nitrogen but the conclusions obtained apply to all tracer gases since their mechanisms of mixing with the air are the same.

In this study, 12 cases of tracer/air mixing in simulated tracer decay tests were computed. Each had different boundary or initial conditions, in terms of inlet air velocity, dimension of the domain, air change rate and initial tracer concentration. Details for each case are listed in Table 1. Note that the small domain dimensions of $0.2\,\mathrm{m} \times 0.2\,\mathrm{m} \times 0.2\,\mathrm{m}$ for cases 1, 2 and 3 reflect sizes of model zones used in wind tunnel testing. In all cases, walls were assumed non-slippery, infiltrating air free from tracer and initial room air stationary.

Table 1 Set-up of computed cases

Case number	1	2	3	4	5	6	7	8	9	10	11	12
Air change rate ac h^{-1}	10	1	0.1	0.1	1	0.25	2.25	0.1	0.1	0.1	0.1	0.1
Zone volume (m^3)	8×10^{-3}	8×10^{-3}	8×10^{-3}	8	8	8	8	8×10^3	8	8	8	8
Velocity (10^{-2} m s^{-1})	2	0.2	0.02	0.2	2	2	2	2	0.8	1.95	13.7	0.2
C_{initial} (%)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1

2.3 Numerical scheme

The Navier–Stokes equations were discretised into finite volume equations, based on three-dimensional Cartesian grids. Denser grids were used closer to the corners and coarser ones away from the corners to limit the total number of cells. The expansion rate of the distance between grid lines was restricted to below 1.2 to promote numerical stability. The computations were time dependant to deal with the tracer concentration decay. However, at the beginning stage of each computation, even the flow pattern is highly transient. So small time steps, usually of $\frac{1}{10}$th of the characteristic time scale based on inlet air velocity, were used. After the computation had proceeded beyond a number of time steps and, as the flow pattern stabilised, the length of the time steps was increased to accelerate the computation. The finite difference equations resulting from the discretisation process were solved using the SIMPLE algorithm. The solution convergence speed was increased by means of the over-relaxation technique after a certain number of iterations/timesteps, during which the solution had shown steady convergence. Fewer iterations per time step were performed as the computation proceeded through the time steps. Eventually this number dropped to around 60 to 100 and at the end of the calculation for each time step, the normalised residuals for the equations were around 10^{-6}.

2.4 Procedure

Before the beginning of each computation, the air in the room was stationary and it had a uniform tracer concentration of 0.1%. As the computation started, supply air with zero tracer concentration entered the room through the inlet while exhaust air left the room via the outlet, as illustrated schematically in Figure 1. The transient velocity and tracer concentration fields for the room were computed and recorded, until the accumulated air infiltration had reached the equivalent of $\frac{1}{3}$rd air change for the room. The room tracer concentration distribution at this moment was then compared with those of other cases (Table 1). The cases can be classified into several groups. In one such group, all the cases were identical except that they had different infiltrating air velocities. By comparing the above described tracer concentration distributions within the group, one can obtain the conclusion regarding the effect of infiltrating air velocity on tracer mixing. Likewise by such comparison within other groups, one can examine the effects of air change rate, building zone size and initial concentration etc., as described in the following sections.

2.5 Result presentation

The tracer concentration distribution results from the CFD computation are best presented using colour- or grey-scale graphics, which facilitate data interpretation as compared with tables of concentration figures. Two examples from this computation are shown in Figures 2 and 3. They show the tracer concentration distributions on the room central plane, indicated in Figure 1, in two computation cases 3 and 1 respectively. The grey scales indicate different levels of tracer concentration. It is obvious from these graphs that the tracer distribution shown in Figure 2 is much more uniform than that in Figure 3. However, despite its user friendliness, this method of data presentation will not be used in the rest of this paper, because to present the tracer distribution in the whole room, one needs, for each computation case, a double-figured number of colour-shaded or grey-scale graphs. Considering the large number of cases in this

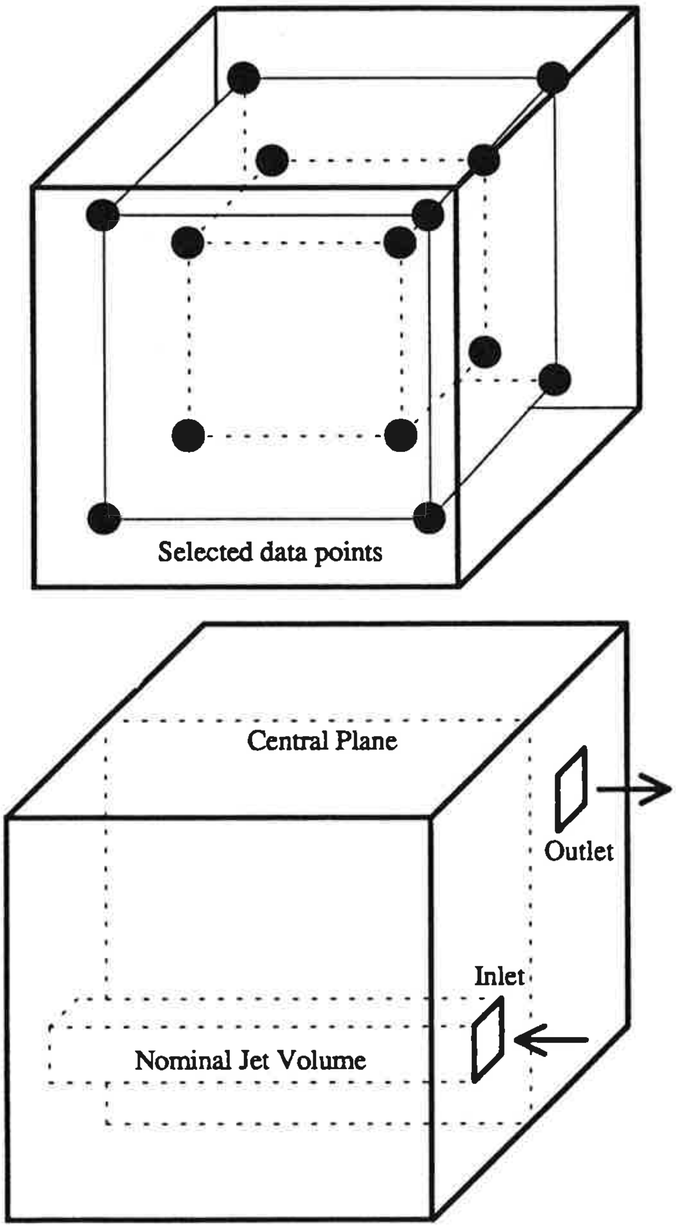

Figure 1 Schematic of the building/zone used in the study

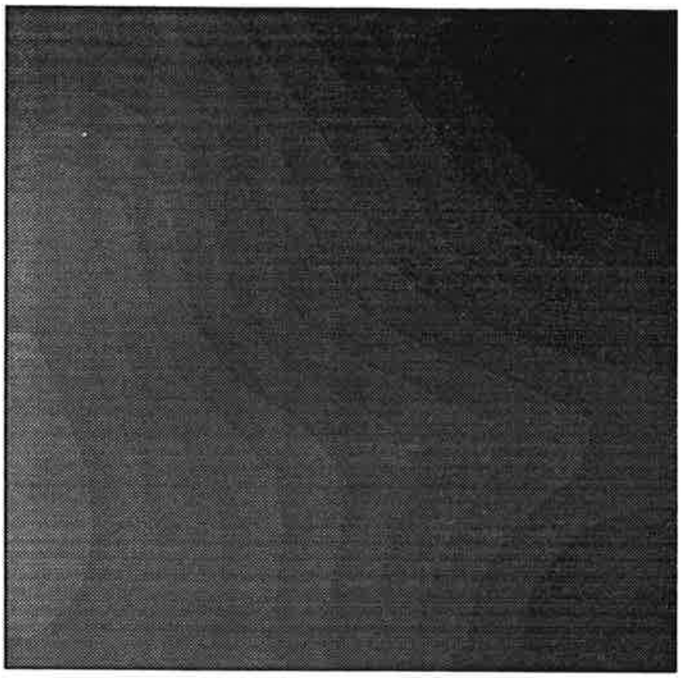

Figure 2 Tracer concentration distribution on the zone central plane for case 3

work, a more efficient method of result presentation should be used. In the following, statistics of the computed results regarding tracer concentration distributions are used instead of the direct presentation of the results themselves. The most often used statistical parameter is the coefficient of tracer concentration variation, k, defined as[3]:

$$k = \left(\iiint_V (C - \bar{C})^2 \, \mathrm{d}x \, \mathrm{d}y \, \mathrm{d}z / V \right)^{0.5} \Big/ \bar{C} \tag{1}$$

where C is tracer concentration; V is the volume of the building zone and $\bar{C}$ is the average tracer concentration, defined as:

$$\bar{C} = \iiint_V C \, \mathrm{d}x \, \mathrm{d}y \, \mathrm{d}z / V \tag{2}$$

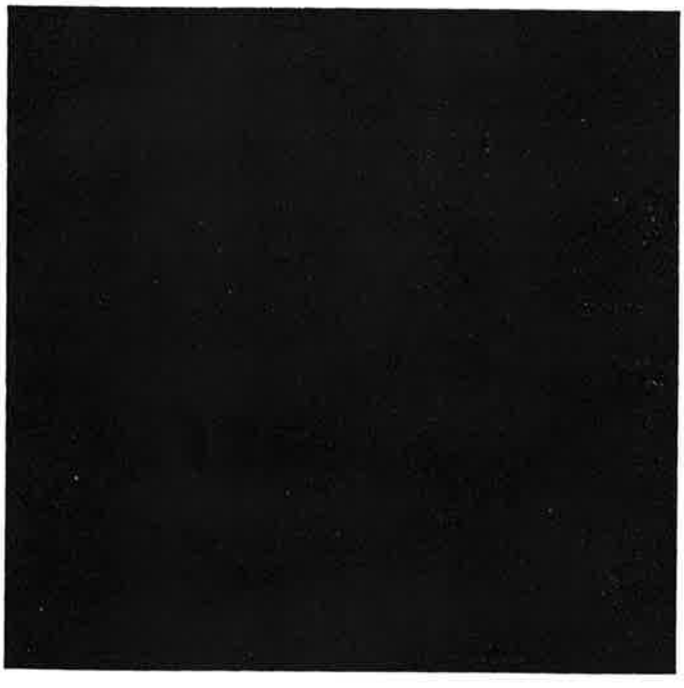

Figure 3 Tracer concentration distribution on the zone central plane for case 1

All tracer concentration values given in this paper are in the unit of volumetric percentage (the percentage of tracer gas in a tracer/air mixture, in terms of volume). Since CFD only provides discrete, instead of continuous, tracer concentration distribution, equations 1 and 2 should be adapted into

$$k = \left[\sum_{n=1}^{N} (C_n - \bar{C})^2 / N \right]^{0.5} \Big/ \bar{C} \tag{3}$$

$$\bar{C} = \sum_{n=1}^{N} C_n / N \tag{4}$$

where N is the number of discrete data points. For this research, tracer concentration at 16 selected points in the room were included to calculate the coefficient of concentration variation. So,

$$N = 16 \tag{5}$$

The positions of the 16 points are indicated in Figure 1. In addition to the above coefficient, another statistical parameter was introduced, namely the coefficient of the spread of tracer concentration, s, which is defined as

$$s = \frac{C_{\max} - C_{\min}}{0.5(C_{\max} + C_{\min})} \tag{6}$$

where $C_{\max}$ and $C_{\min}$ are the maximum and minimum tracer concentrations respectively, in the building zone. Since the infiltrating air has no tracer content, it is virtually inevitable that $C_{\min}$ be found near the inlet and has the value 0. However, this uniform value conceals the differences between the cases in terms of tracer/air mixing performance. To counter this problem, the minimum tracer concentration in the rectangular grid tube immediately envircling the nominal infiltrating air jet volume (Figure 1) was taken as the $C_{\min}$ used in equation 6. Note that this restriction only applies to CFD results because experiences showed that in a real tracer test, only limited number of samples are taken and few people take samples close to boundaries, therefore there is little chance of encountering the zero concentration problem described above.

The coefficient of tracer concentration spread, or spread coefficient, was used to complement the coefficient of tracer concentration variation, or variation coefficient, which although used more often, does have certain limitations. First, it provides only the averaged deviation of tracer concentration from the averaged concentration, and thus does not reflect the true extent of tracer concentration variation. The latter is probably more important for evaluating the tracer/air mixing performance and thus the tracer gas test accuracy. Second, in this study, as in most such studies, concentrations at a few selected fixed locations (as opposed to continuous distribution) were included in the calculation of k. As a result of the limited number used, the k thus calculated, referred to in the following as the discrete k, could be significantly different to the k based on a continuous distribution or the full set of CFD concentration distribution data, referred to as the continuous k. Since concentration distribution may follow different patterns in different cases, the discrete k values in these cases, though based on the same set of locations, may deviate by different degrees from the corresponding continuous k values. Consequently, they may not be comparable to each other, although, by increasing the number of the locations, this problem can be alleviated. The second point will be discussed again later. In contrast, the spread coefficient is free from these two problems: it shows the true extent of tracer concentration by incorporating only the two extremes into its calculation and for the same reason it avoids the dependency of its value on the choice of data point locations. However, it should be said that by including only the two extremes, the spread coefficient does not convey any information on the most probable extent of tracer concentration variation as the variation coefficient does. Actually, some of the extreme concentrations tend to occur near corners and often relate to a relatively small percentage of the air in the zone.

The above discussion shows the mutually complementary nature of the two parameters. They should be used simultaneously in evaluating tracer/air mixing performances. From the definition of the above two parameters, it is clear that the smaller their values, the more uniform the mixing. In the extreme case of them being zero, the tracer concentration distribution will be completely uniform and the relative error in tracer gas measurements due to tracer mixing will be zero. Since such a situation never actually happens, questions arise as to whether there exist critical values of the above parameters below which the tracer distribution uniformity is acceptable in terms of the tracer gas method accuracy and, if they do exist what are they. It has been claimed by Turk *et al.*(11) that if the variation coefficient is below 10% then tracer/air mixing is satisfactory. However, as pointed out by Alevantis and Hayward(3), this figure has no physical basis and should be treated as an arbitrary assumption. A thorough study of this issue, although important, is beyond the scope of this paper. The following discussion will be restricted to the relative tracer/air mixing performance, for which it is sufficient to know that lower spread and variation coefficients indicate better mixing.

3 Results and discussion

3.1 *Effect of air change rate*

As mentioned in the introduction, the effect of air change rate on tracer concentration distribution has been studied experimentally by Alevantis and Hayward(3). Tests were performed on four real buildings, which had two to four storeys and total floor areas of between 2000 and 11 100 m^2. Tracer concentrations were measured at several locations in each building and were used to calculate the coefficient of tracer concentration variation for the corresponding building. The total number of such locations for each building varied from two to six. It was found that at low ventilation/infiltration rates of below 0.5 ac h^{-1} the mixing was satisfactory, i.e. the corresponding coefficients were below 10%, but at air change rates of 1 ac h^{-1} and over, satisfactory mixing was not achieved on a consistent basis. This critical air change rate of either 0.5 or 1 ac h^{-1} has been examined by computing the cases in groups 1, 2 and 3. The cases in Group 1 have identical conditions except that the air change rate was varied from 0.1 ac h^{-1} to 1 ac h^{-1} and then to 10 ac h^{-1} by varying the velocity of the infiltrating air stream. As can be seen from Table 2, both the variation coefficient and spread coefficient drop with the air change rate, indicating better mixing. Furthermore, the results apparently support the findings of Reference 3, with variation coefficients of 0.71% and 7.0% for 0.1 ac h^{-1} and 1 ac h^{-1} respectively but 28.5% for 10 ac h^{-1}. Another interesting phenomenon is the large differences between the corresponding spread coefficient and variation coefficient figures. Note $s = 77.5\%$ and $k = 28.5\%$ at 10 ac h^{-1} and $s = 39.4\%$ and $k = 7.0\%$ at 1 ac h^{-1}. These differences demonstrate the extent by which the variation coefficients conceal the true levels of tracer concentration variation.

The above examination was repeated for a larger zonal volume by computing the cases 4 and 5 in Group 2. Again air change rate was varied, from 0.1 to 1 ac h^{-1}. As shown by the results in Table 2, the spread coefficient and variation coefficient figures confirm that the mixing improves with decreasing air change rate. However, the results showed that, contrary to the claims of Reference 3, even at 0.1 ac h^{-1}, the mixing was not 'satisfactory', with k at 28.8%, well above the 10% mark. This can be conceptually explained as follows.

The two zones in Group 1 and Group 2, now named zone 1 and zone 2, are geometrically similar. Suppose zone 2 is larger than zone 1 by a factor of α in every dimension, then with a degree of approximation and dropping the proportionality coefficient, the following can be written:

$$F = DAg_C \tag{7}$$

$$\therefore \quad F_1 = DA_1 \frac{C_{01}}{R_1} \tag{8}$$

$$F_2 = DA_2 \frac{C_{02}}{R_2} = D\alpha^2 A_1 \frac{C_{01}}{\alpha R_1} = \alpha F_1 \tag{9}$$

where F is the rate of the diffusion of tracer from room air into the fresh infiltrating air, D is binary diffusivity, A is the nominal infiltrating air jet surface area, g_C is the gradient of tracer concentration, C_0 is initial tracer concentration and R the equivalent radius of the infiltrating air jet. Equation 9 shows that as the zone dimension increases by a factor of α, so does the capacity of tracer diffusion or mixing. However, the zone enlargement

Table 2 Statistical results from the computation showing the effect of air change rate on tracer mixing

	Group 1			Group 2			Group 3	
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 5	Case 7
Air change rate ac h^{-1}	10	1	0.1	0.1	1	0.25	1	2.25
$C_{\max}$ ($\times 10^{-2}\%$)	9.70	8.01	7.82	9.77	9.99	9.32	9.99	9.99997
$C_{\min}$ ($\times 10^{-2}\%$)	4.28	5.00	7.44	3.60	3.05	5.54	3.05	2.37
Spread coefficient (%)	7.5	39.4	5.0	92.3	106	50.9	106	123
Variation coefficient (%)	28.5	7.0	0.71	28.8	37.5	22.2	37.5	48.5

leads to the increase of the amount of tracer to be diffused, m, by a factor of α^3,

$$m_2 = C_{02} V_2 = C_{01}(\alpha^3 V_1) = \alpha^3 m_1 \tag{10}$$

greatly outpacing the increase of diffusion or mixing capacity. As a result, the relative capacity of tracer diffusion/mixing actually decreased by a factor of α^2 which in turn causes the poorer tracer/air mixing as witnessed in the computation results for the larger zone.

Both the computation and the analytical results show (contrary to the claim of Reference 3) that there is not a universal value of air change rate below which tracer mixing is consistently satisfactory. In other words, there are other factors affecting the mixing (e.g. zone volume), which will be discussed in the following sections. It is likely that the above contradiction is due to the limited number of sampling points used in each building in the study presented in Reference 3. Tracer concentrations from a maximum of six locations were used to draw conclusions about the tracer concentration distributions in buildings with as many as six storeys and 11 100 m^2 of floor area. While the number of sampling points was hardly sufficient and the results hardly reliable, it should be pointed out that simultaneously measuring concentration at six points is approximately the 'state of the art' and the practical limit in terms of equipment costs. Hence the difficulty of experimentally investigating tracer/air mixing is again demonstrated clearly.

Although the concept of an air change rate threshold in terms of satisfactory mixing is ill-founded, lower air change rates, as shown above, do lead to more uniform tracer distribution. This seems obvious, since with a lower air change rate, there is less fresh air to diffuse into the room air/tracer mixture for the same length of time and so the concentration distribution should be more uniform. However, the full picture is more complicated and a conceptual explanation may not be possible. In certain situations, as in the cases computed above, the higher air change rate was accompanied by higher infiltrating air velocity. Although there was more fresh air to diffuse, there was also a higher diffusion capacity associated with the higher velocity (see section 3.3).

To exclude the effect of different velocities, another group (Group 3) of cases (5, 6, 7) was computed. The infiltrating air stream velocities were the same for the three cases and their corresponding air change rate was varied from 0.25 ac h^{-1} to 1 ac h^{-1} and then to 2.25 ac h^{-1} by means of varying air inlet area. As can be seen in Table 2, when air change rate increases, the spread coefficient climbs from 50.9% to 106% and then to 123% while the variation coefficient also moves up from 22.2% to 37.5% and then to 48.5%. These results confirm the positive effect of lower air change rate on tracer/air mixing.

3.2 Effect of building zone volume

The effect of building zone volume was studied by computing the cases 3, 4 and 8 in Group 4. The volume for case 4 was 10^3 times that for case 3 and the volume for case 8 was 10^3 times that for case 4. All the zones were geometrically similar and all other conditions were the same except velocity which had to increase to keep other parameters identical for the cases. As part of the discussion in the previous section, it has already been shown, both computationally and analytically, that increasing the volume of the building zone has a negative effect on mixing. This is again confirmed. The results given in Table 3 show that when the zone dimension increases by 10 and then by 100 times, the spread coefficient follows, moving from 5% to 92.3% and then to 104% indicating poorer mixing. The variation coefficient also increases, at first from 0.71% to 28.8% then to 36.1%.

Table 3 Statistical results showing the effect of zone volume on tracer air mixing

	Group 4		
	Case 8	Case 4	Case 3
Zone volume (m^3)	8×10^3	8	8×10^{-3}
C_{max} ($\times 10^{-2}$%)	9.88	9.77	7.82
C_{min} ($\times 10^{-2}$%)	3.11	3.60	7.44
Spread coefficient (%)	104	92.3	5.0
Variation coefficient (%)	36.1	28.8	0.71

3.3 Effect of velocity of infiltrating air stream

There are two kinds of driving force behind tracer/air mixing, namely the laminar mixing due to the diffusion of the tracer and air component molecules and the turbulent mixing due to the entrainment action of the turbulent eddies. While the first mixing mechanism depends largely on the local concentration gradients and is not related to air velocity, the second is, as shown by the following.

The strength of turbulence and hence that of turbulent mixing can be evaluated with turbulence kinetic energy. According to the theory of turbulence,

$$P_{EK} = -\langle u_i u_j \rangle \frac{\partial U}{\partial x_j} \tag{11}$$

where P_{EK} is the turbulence kinetic energy production; $\langle u_i u_j \rangle$ represents the Reynolds stresses and $\partial U/\partial x_j$ are the shears in the mean velocity field. Equation 11 shows that turbulence kinetic energy is produced by the working of the Reynolds stresses against the mean shears. Particularly, it points out that turbulence kinetic energy production is proportional to the mean velocity gradient, which for these cases of air infiltration increases with increasing air velocity of the infiltrating stream. Thus, the produced extra turbulence kinetic energy, or turbulence strength, in turn improves the tracer/air mixing.

The prediction above of the positive effect of increasing air velocity on tracer/air mixing has been scrutinised by computing cases 4, 9, 10 and 11 in Group 5. Inlet air velocities for case 9, case 10 and case 11 were 4, 10, and 69 times that for case 4. All other conditions including air change rate, building zone volume and initial concentration were identical for all four cases. The results in Table 4 show that as the inlet velocity increases, the spread coefficient drops from 92.3% for case 4 to 44.8% for case 9, 44.2% for case 10 and then to 40.9% for case 11. In addition the corresponding variation coefficients for the four cases also drop from 28.8% to 10.3%, 8.2% and then to 4.3%. These results reinforce the finding above, that mixing improves with increasing velocity of the infiltrating air stream.

Table 4 Statistical results showing the effect of inlet air velocity on tracer air mixing

	Group 5			
	Case 4	Case 9	Case 10	Case 11
Inlet air velocity ($\times 10^{-2}$ m s^{-1})	0.2	0.8	1.95	13.7
C_{max} ($\times 10^{-2}$%)	9.77	8.93	8.32	7.16
C_{min} ($\times 10^{-2}$%)	3.60	5.66	5.31	4.73
Spread coefficient (%)	92.3	44.8	44.2	40.9
Variation coefficient (%)	28.8	10.3	7.4	4.3

3.4 Effect of initial tracer concentration level

In a standard tracer decay test, an amount of tracer is first released in the zone to be tested. Then it is thoroughly mixed with air in the zone to achieve uniform tracer concentration across the zone before the decay measurement starts. This uniform concentration is referred to as the initial concentration level. In a practical situation depending on the amount of tracer released, the infiltration strength and the time used in achieving the uniformity, the initial concentration levels vary, probably significantly. The effect of such variation on tracer mixing uniformity afterwards was examined by calculating the cases 4 and 12 in Group 6. Results showed that the effect is negligible as long as the tracer concentration is low (below 1%). As seen from Table 5, both the spread coefficient and the variation coefficient values for the two cases are identical.

4 Conclusions

Both the analytical and computational results have shown that air change rate is not the only factor affecting tracer/air mixing and therefore there is not a universal critical value of air change rate below which satisfactory mixing is guaranteed.

In addition to the air change rate, other factors studied included the building zone volume, the velocity of the infiltrating air stream and the initial tracer concentration. It was found that lower air change rate, smaller zonal volumes and higher infiltrating air velocity have positive effects on the uniformity of tracer/air mixing. The initial tracer concentration, provided it is sufficiently low (e.g. 1%), shows no effect.

The above analysis was performed with the intention of examining the problem of tracer/air mixing, information on which, although important and much needed, has been scarce due to experimental difficulties. The above conclusions are not meant to be definitive verdicts and it is felt that it would be beneficial that the above results be put to experimental examination as facilities for doing so become more readily available.

Table 5 Statistical results showing the effect of initial tracer concentration on tracer air mixing

	Group 6	
	Case 4	Case 12
Initial tracer concentration (%)	0.1	1
C_{max} (%)	9.77×10^{-2}	9.77×10^{-1}
C_{min} (%)	3.60×10^{-2}	3.60×10^{-1}
Spread coefficient (%)	92.3	92.3
Variation coefficient (%)	28.8	28.8

The analysis is by no means exhaustive. There are other factors affecting tracer/air mixing, two important classes of which are the building zone shapes and position of the inlets/outlets for infiltration/ventilation air streams. Since there are a great variety of building shapes and air flow paths, but limited computing resources, the inclusion of an examination of their effects in this work has not been possible. It is felt necessary that before such a study is carried out, the common variations of building zone shapes and likely positions of air flow inlet/outlets be identified. One promising technique for the latter is the infrared imaging method currently being developed at Sheffield University$^{(12)}$.

Finally, it is worth mentioning that the spread coefficient and the variation coefficient should be used together for assessing tracer/air mixing. The former provides the true extent of tracer concentration variation while the latter shows the average variation level.

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