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The Role and Application of Ventilation Effectiveness in Design

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ABSTRACT

Ventilation effectiveness provides a means for assessing the performance of ventilation systems. However, the evaluation of indices of ventilation effectiveness relies heavily on measurement methods. This, therefore, tends to restrict the applicability of such an approach to diagnostic investigations on existing buildings. Recent advances in computational fluid dynamics (CFD) have resulted in the development of algorithms which may be used to predict air flow and pollutant transport within buildings. The application of such algorithms may therefore be used in place of measurement methods to evaluate ventilation effectiveness. Thus by combining CFD with the concepts of ventilation effectiveness, it is possible to assess ventilation effectiveness as part of the design process. The purpose of this paper is to review developments within this field and to demonstrate results by introducing some simple examples.

KEYWORDS

Ventilation Effectiveness, Computational Fluid Dynamics, Design

INTRODUCTION

The pattern of airflow within a building or within individual zones or rooms can have a considerable impact on ventilation energy performance. In addition, the behaviour of airflow influences the propagation of airborne pollutants, the thermal environment and general comfort conditions. In order to optimise design and to ensure a healthy interior, increasing attention is being focused on analysing building airflow behaviour, especially in relation to understanding the mixing characteristics of air and pollutants.

In practice, such an analysis is an extremely complex task; such factors as the presence and distribution of leakage openings, the location of supply and extract terminals, room layout, occupant patterns and the location and strength of heat and pollutant sources all combine to exacerbate the problem.

In existing structures, ventilation effectiveness measurements provide a valuable solution. Such measurements may be used to determine the degree to which fresh air is circulated and mixed within the occupied zone as well as to determine how ventilation air interacts with pollutants. However, these measurement results are unique to the enclosure and to the circumstances prevailing at the time of measurement. It is therefore extremely difficult to apply such results to general design applications. Recently, increasing interest has been shown in the use of computational fluid dynamics (CFD) to predict and analyse building flow problems. Potentially, this technique offers substantial benefits, since an almost infinite range of ventilation configurations and room designs may be evaluated at the design stage. CFD results, however, are extremely complex, culminating in three dimensional arrays of velocity components, temperature values and pollutant concentrations. While qualitative output in the form of 3-dimensional graphics can provide a very powerful illustration of the ventilation process, a simplified quantitative representation of results is still needed. This may be achieved by combining the results of CFD with the definitions of ventilation effectiveness. The objective of this paper is to review and evaluate the application of ventilation effectiveness concepts combined with computational fluid dynamic approaches in the design and assessment of ventilation performance. Simple examples illustrating the combination of flow field prediction with ventilation effectiveness are presented. The basic principals of ventilation effectiveness are also reviewed.

VENTILATION EFFECTIVENESS

Ventilation plays a key role in the dilution and removal of pollutants within occupied spaces. Minimum requirements are frequently set to meet the metabolic needs of occupants. Added to such requirements are those needed to dilute other sources of pollutant such as moisture, tobacco smoke and emissions from office equipment. Requirements and recommendations within the office environment vary enormously. ASHRAE (1989) in the United States, for example, recommend a rate of between 10 l/s.person for office spaces to 30 l/s.person for smoking rooms. In the United Kingdom, CIBSE (1986) recommend rates varying from 8 l/s.person in non-smoking areas to 32 l/s.person in areas of heavy smoking. Many Standards and requirements in other countries also outline similar ventilation needs as summarised by Colthorpe (1990). Unfortunately, ventilation can impose a high energy load which often represents a significant proportion of a building's total energy needs. Furthermore, ventilation systems are expensive to install and maintain, and, in addition, occupy valuable floor space. There is hence an advantage in minimising ventilation needs by restricting pollutant emissions and by developing efficient ventilation designs. The concepts of ventilation effectiveness provide a useful method of quantifying the performance of ventilation in buildings.

Ventilation efficiency may be regarded as a series of indices or parameters which indicate the mixing characteristics of incoming air with air already present within an enclosure and which characterise the pollutant distribution resulting from the interaction of airflow with internal pollutant sources. These two aspects may be subdivided into indices of air change efficiency and pollutant removal effectiveness respectively (Sandberg and Skaret 1985). This approach enables the performance of a ventilation system to be assessed in terms of both providing fresh air to occupants and in diluting and/or removing pollutants from a space. Since pollutants are often spatially distributed, it is also necessary to consider specific locations within a room such as the "breathing" or "occupied" zone.

No attempt is made in this paper to give a comprehensive account of ventilation effectiveness, since this is covered by other authors (Sandberg 1991, Skaret 1984). Recent reviews on terminology associated with air change efficiency and contaminant removal effectiveness have also been written by Sutcliffe (1990) and Brouns and Waters (1991). Instead, some basic principals are considered, firstly, in relation to air change efficiency and, secondly, in relation to pollutant removal effectiveness. Following this account, the role of CFD analysis in predicting ventilation effectiveness indices is reviewed.

AIR CHANGE EFFICIENCY

In much design work, ventilation air is assumed to be well mixed and needs are based on the assumption that incoming clean air mixes uniformly and instantly with that already present within the space. In practice, this situation is often not achieved. Obstructions caused by room layout, the short circuiting of air between supply and exhaust points as well as disturbances to airflow patterns created by thermal sources, may contrive to prevent good mixing. Furthermore, modern designs often seek to avoid the mixing of fresh air with room air; instead a displacement or piston flow approach is preferred. The analysis of air change efficiency takes on a vital role when, either through design or circumstances, there is a departure from perfect mixing.

In general, the quality of air in a space will be dependent on the length of time that it is present within that space. In other words, as the "age" of air increases, it becomes more probable that it absorbs increasing amounts of pollutant. The time it takes for air to be completely renewed is defined as the "air change time". Ultimately, the minimum air change time is governed by the rate of ventilation itself. In considering ventilation effectiveness, it is therefore common to express ventilation rate in terms of "time". This may be readily accomplished by introducing the idea of "specific flow" which, for a ventilation rate of Q m3/s in an enclosure of volume, V m3, is given by:

$$S=Q/V \qquad (1/t) \qquad (1)$$

The inverse of this is defined as the "Nominal Time Constant", which represents the minimum time in which air in an enclosure can be replaced.

Under conditions of perfect mixing, it may be shown that the air change time is equal to twice the nominal time constant (Sandberg and Sjoberg 1983) and therefore, arguably, perfect mixing does not represent the most "efficient" approach to air replacement. Piston or displacement flow, on the otherhand, achieves this target. If air is trapped at a location, then the air change time will increase, indicating a zone of poor mixing. The overall mixing characteristics of the system can be expressed in terms of "Air Change Efficiency". This is simply given by the percentage ratio between the nominal time constant and the air change time. It therefore provides a measure of how quickly air in an enclosure is replaced under different conditions of mixing. Less than 50% implies short circuiting or the retention of air in part of the space, 50% implies perfect mixing, while 100% indicates piston flow.

While the value of air change efficiency may indicate a mixing problem within a space, it will not indicate where the problem exists. Only by monitoring the age of air at specific locations within a zone can the location of poor mixing be found. This "local mean age" is defined as the average time it takes for air to travel from the point of entry into an enclosure to the location of interest. From these principal definitions, virtually all other indices related to air change efficiency may be derived.

POLLUTANT REMOVAL EFFECTIVENESS

While the age of air can give some indication of the likelihood of poor air quality, much depends on the emission strengths and locations of pollutant sources. Thus for good ventilation design, much more is needed to be known about these factors. Ideally, the ventilation system should provide air to occupants with the minimum of contamination. In the case of mixing ventilation, the nominal time constant must be sufficiently short to ensure the adequate dilution of pollutant. In the case of displacement systems, air upstream of the occupant should remain unpolluted, while, once free of the occupied zone, pollution concentration is of less significance. A pollutant source located at the supply point, for example, will contaminate all incoming air. On the otherhand, a pollutant source close to the extract point will leave the leave much of the remainder of the enclosure free of contaminant. Thus, even when conditions of air change efficiency are seemingly satisfied, the location of pollutant sources may destroy the benefits of the system. These aspects are covered by indices of pollutant removal effectiveness.

Many of the terms associated with pollutant removal effectiveness are analogous to those used to describe air change efficiency. The concept of "time" is applied starting with the "nominal time constant for the contaminant". This is also known as the "turnover time" of contaminant or the "transit time". It is the average time it takes for contaminant to flow from its source to the exhaust point of an enclosure. Other important indices include the "contaminant removal effectiveness", the "contaminant removal efficiency" and the "local air quality index". The first of these indices is derived from the ratio of steady state concentration of contaminant at the exhaust duct and the steady state mean concentration of the room. Complete mixing of pollutant corresponds to a contaminant removal effectiveness of unity, while piston flow will have a greater value and short circuiting will yield a lower value. Contaminant removal efficiency is simply a normalised version of contaminant removal effectiveness, in which perfect mixing of pollutant takes on a value of 0.5. The local air quality index is defined as the ratio of the steady state concentration of contaminant at the exhaust and the steady state concentration at a specific location. A high index value may therefore be associated with low contaminant concentration. This latter quantity is especially important because it defines the spatial distribution of air quality conditions. As with air change efficiency, other indices exist which these can be derived from this basic set of definitions.

MEASURING VENTILATION EFFECTIVENESS

Hitherto, indices of ventilation effectiveness have been evaluated by means of tracer gas analysis. Three techniques are common; these are:

- pulse injection, in which the propagation of a short pulse of gas, injected into the supply duct, is monitored.

- step-up method, in which the time variant concentration of gas is monitored following constant injection into the supply duct.

- tracer decay, in which the concentration decay is monitored following the uniform mixing of tracer gas within the space.

Room average values of air change and contaminant removal effectiveness can be evaluated by monitoring tracer gas at the exhaust location, thus avoiding the need to make measurements at many points throughout the space. While these results will indicate that poor mixing or pollutant problems within the space exist, they cannot be used to identify the location. This can only be achieved by making measurements of tracer concentrations at specific locations.

The measurement steps are illustrated in Figure 1. Data input includes ventilation rate and room volume, for the evaluation of specific flow and nominal time constant, and the location of supply and extract points, for injection and monitoring purposes. In theory, measurements may be applied to naturally ventilated buildings, but complete knowledge of openings and flow rates is needed. Air change efficiency is evaluated using one or more of the listed tracer gas methods. Pollutant removal effectiveness is evaluated either by monitoring the pollutant itself or by using tracer gas to represent location and source strength. More details on measurement techniques are summarised by Sutcliffe (1990) and Brouns (1991).

CALCULATING VENTILATION EFFECTIVENESS

The calculation of ventilation effectiveness follows similar steps to that of measurement (Figure 2) but predictive techniques are used to replace tracer gas. Apart from some very simple configurations, numerical methods, based on computational fluid dynamics are necessary. These methods are used to solve the equations of flow, turbulence and pollutant transport. Solution involves discretising the enclosure or space into a series of control volumes or elements in which the transport equations are represented by discretised approximations. Computational fluid dynamics relies on the ability to express each transport equation (ie flow, turbulence, pollutant transport etc) in an identical form. A full description of CFD techniques is presented by Shih (1984). From consideration of both the transient movement of air and the predicted steady state distribution of pollutants, all indices of ventilation efficiency may be derived from CFD solutions. Since measurement data are not needed, predictions can be made for almost any building design and operating conditions. A further important advantage of this approach is that flow and pollutant conditions are evaluated for every control volume. This will typically represent many thousands of locations throughout the space and will be well beyond the number of measurements that would be practicable within the same space. Thus complete maps of local indices of air quality and mean age can be produced.

EXAMPLES

Three examples have been selected to illustrate the role of calculation and to illustrate the influence of ventilation on air change efficiency and pollutant removal effectiveness. The first is based on a simple analysis of complete mixing in a well defined enclosure. A similar enclosure is then considered in which piston flow is assumed. This second example is greatly simplified by assuming a well defined flow field and pollutant source. Finally, the third example focuses on a more general problem involving mixed convection, flow obstructions, and occupants. This latter example demands the rigorous use of CFD.

Example 1 Perfect Mixing

Figure 3 illustrates an office enclosure of height, H(m), and volume, V(m3), in which an item of equipment, located at a height of 1/3H, produces pollutant at an emission rate, P. A ventilation rate of Q m3/s is assumed. Two occupants are present within the office, one is operating the equipment and the other is located some distance away. The surface area of polluting source was assumed to be 1/50 th of the floor area. The objective of this example is to evaluate overall air change efficiency and the local air quality index at the location of both the equipment operator and the sedentary worker.

Example 2 Vertical Piston Flow Air Movement

An identical enclosure is depicted in Example 2, as illustrated in Figure 4. This time, however, the mixing ventilation is replaced by a vertical piston flow ventilation pattern. Again, the objective is to evaluate the air change efficiency and the local air quality index in the vicinity of both the equipment operator and the remote sedentary worker.

Example 3 CFD Analysis

The above results are very idealised but, nevertheless, represent the limit to which these concepts may be applied without the use of numerical techniques or measurement. This third example is intended to illustrate the application of CFD techniques to a more typical environment. The algorithms chosen for this example were EXACT3 for the prediction of 3-dimensional airflow and CONTAM3 for the prediction of pollutant transport. Both codes were developed by Kurabuchi et al (1990). This example was analysed using a 486 "PC" computer running at 33 MHz with a Weitec co-processor.

A plan view of the network is illustrated in Figure 5. This Figure represents a 5x10x2.75m office with four occupants and associated furniture, lighting, ventilation and heating. Supply air is injected at low level, while exhaust air is extracted at ceiling level. Heat is generated by room heaters, lighting and the occupants. Heat loss occurs through each of the vertical walls. Thus the configuration is one of non isothermal mixed convection. In order to simplify the problem, symmetry has been applied and inlets and outlets have each been restricted to four control volumes. The CFD model was used to predict the pattern of metabolic carbon dioxide concentration for a typical set of operating conditions. From this, the contaminant removal effectiveness, the contaminant removal efficiency and the local air quality index has been derived.

RESULTS AND DISCUSSION

The first two examples represent almost the limit to which air change efficiency indices can be evaluated without recourse to measurement or numerical techniques. The first example, being of perfect mixing, is trivial, yielding a ventilation efficiency of 50% and a local air quality index, at all locations, of unity. Thus, both the equipment operator and the remote sedentary worker receive the same dose of pollutant. Assuming no external source, the equilibrium concentration of pollutant, C, is given by:

$$C = P/(Q+P) \tag{2}$$

where P = emission rate of pollutant
Q = ventilation rate

It is further assumaed that $Q>>P$, then equation(2) reduces to:

$$C = P/Q \tag{3}$$

Reduction of pollutant concentration can only be achieved by reducing the emission rate, P, from the equipment or by reducing the nominal time constant by increasing the ventilation rate, Q.

In the second example, the pollutant is entrained by the non mixing, vertical flow pattern. The volume of air in which the pollutant mixes is extremely reduced, while, at the same time, the quantity of ventilation air to which the pollutant is exposed is also substantially reduced.

In consequence, while the sedentary occupant is now relatively free of pollutant, the operator standing over the pollutant source will be exposed to a much greater concentration. The pollutant concentration may be approximated by considering that the source occupies 1/50th of the floor area. Since no mixing of air occurs, the ventilation air available to dilute the pollutant is Q/50. Hence, by substituting into equation 3, the pollutant concentration to which the operator is exposed is approximately 50 times greater than in example 1. The Local Air Quality Index is thererfore very high for the sedentary worker, but only 0.02 for the machine operator

While the above two examples enable a conceptual evaluation of very simple problems to be made, they do not permit detailed design work. The third example represents a more realistic configuration of the type that may be readily analysed using CFD analysis. A carbon dioxide contaminant contour plot for this example is presented for two planes in Figure 6. These cut through the two occupants in the Y plane and through the far occupant in the Z plane. The emissions from the two occupants may be clearly observed as can the movement of carbon dioxide towards the extract point. The "piston" or "displacement" concept is also in evidence with very little pollutant approaching the supply points.

CONTAM3 calculates a room averaged value of pollutant and the concentration of pollutant for each control volume. From these data all indices of pollutant removal effectiveness may be evaluated.

The basic results are summarised in Table 1 below.

Table 1 Calculated Pollutant Removal Effectiveness Indices

Carbon Dioxide Concentrations (normalised with respect to exhaust value):	
Exhaust Concentration	1.0
Room Average Concentration	0.6
Maximum Concentration	3.0
Location of Maximum Concentration:	Above Occupants
Calculated Indices:	
Contaminant Removal Effectiveness	1.67
Contaminant Removal Efficiency	0.62
Local Air Quality Index (breathing zone)	0.33

The derived contaminant removal efficiency of 0.67 confirms a tendency towards piston flow of pollutant. However, the local air quality index of 0.33 indicates, that the carbon dioxide concentration within the "breathing" zone, is three time greater than at the exhaust point. This has interesting consequences if a demand controlled carbon dioxide monitoring system located in the exhaust duct is planned. Clearly, concentration at the exhaust would underestimate conditions close to the occupant.

The CFD approach therefore enables a fairly complex office environment to be analysed with relative ease. Different pollutant sources and locations, as well as alternative ventilation configurations and room layouts, may be readily analysed. It should be stressed, however, that results are dependent on the many assumptions that are required of CFD code. These concern discretisation density, boundary flow characteristics, turbulent intensity and pollutant diffusion characteristics. Such aspects require much subjective judgment and, therefore much further verification work is needed before such an approach may be used with confidence.

CONCLUSIONS

Indices of ventilation effectiveness provide a means to assess and quantify the performance of ventilation systems. Historically, these indices have been developed and based on the results of tracer gas measurements. In consequence, the value of this approach has largely been restricted to evaluation and diagnostic studies on existing structures. Because ventilation effectiveness is a unique function of building layout and operating conditions, it is has not been generally possible to transfer results derived from measurements to design applications. However, recent developments in computational fluid dynamics have enabled measurement results to be replaced by numerical predictions, thus enabling the concepts of ventilation effectiveness to be applied at the design stage. Potentially, CFD offers many other advantages, since it may be used to analyse many room configurations as well as to explore the changes to flow caused by thermal sources, flow impedances and ventilation configurations. Additionally, since the enclosure is subdivided into many control volumes, the variation in airflow and pollutant parameters throughout the space may be readily evaluated and sampled at many more locations than is possible by tracer gas. The CFD example presented in this paper has been used to demonstrate such an approach. These computational methods thus unlock the potential of ventilation effectiveness as a design concept. Ventilation effectiveness also provides an essential method of summarising the results of CFD analysis.

The increasing availability of CFD code for operation on small 'PC' computing systems means that they are becoming available to the designer. However, a high degree of specialist skill is still necessary for their optimum application. Much judgment is needed in relation to assessing the value of the many empirical values associated with flow, turbulence and contaminant transport characteristics. Further validation is therefore essential as is guidance on the appropriate use of empirical inputs.

Detailed validation of numerical flow models is a complex task involving comprehensive flow measurements in test chambers. While such an exercise is vital for assessing and improving the detail of flow field prediction, the necessary measurement data will remain very limited for the foreseeable future. Assessing the performance of CFD analysis for predicting ventilation effectiveness indices need not, however, involve such complexity. Instead, immediate use can be made of the already vast database of existing ventilation effectiveness measurements. These include data for well defined real buildings as well as data for test structures. While such an approach precludes detailed flow comparisons, it would nevertheless verify the use of CFD for general ventilation design. It is proposed that activity in this area of validation should be considered.

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Figure 1 Measuring Ventilation Effectiveness

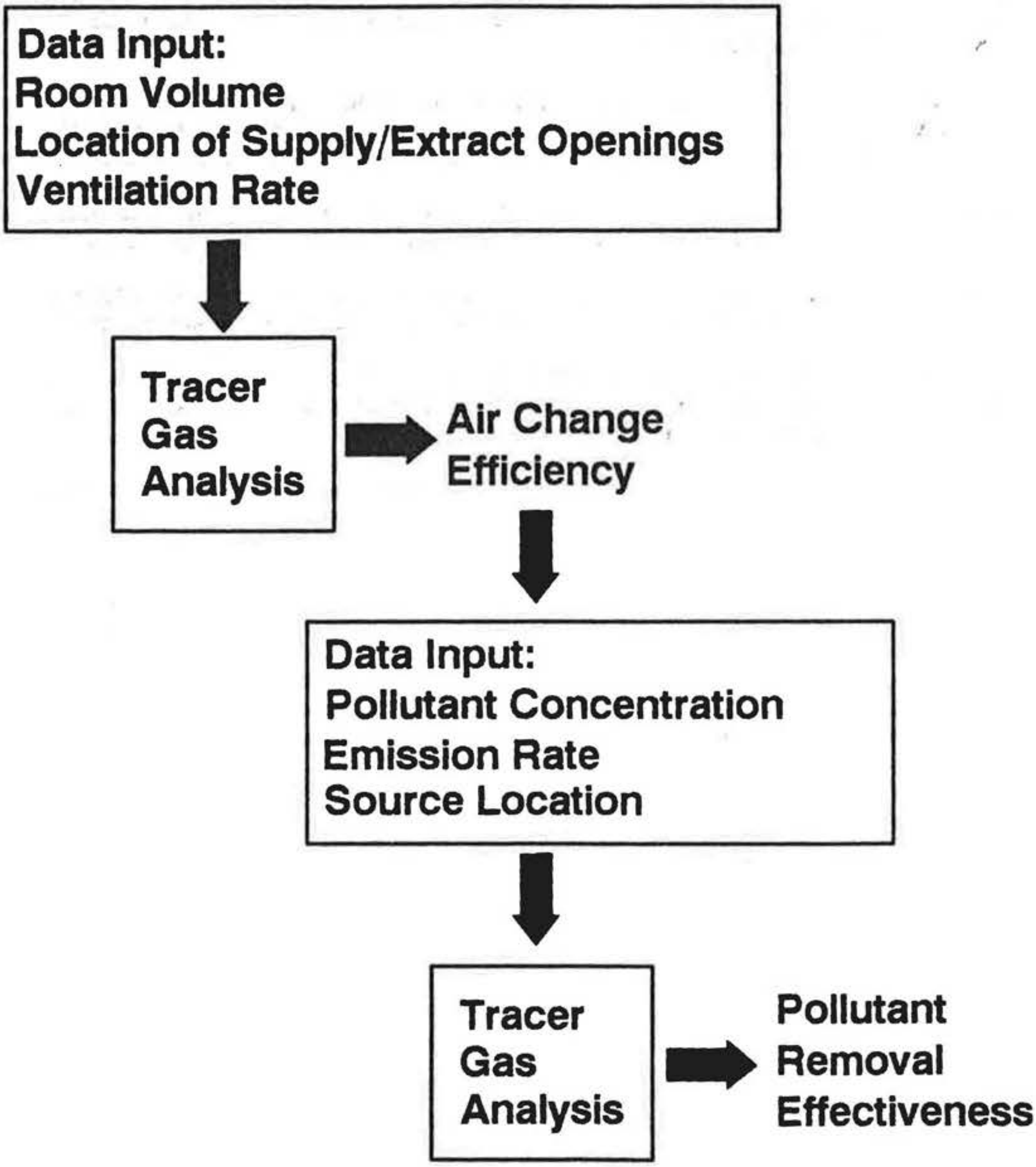

Figure 2 Calculating Ventilation Effectiveness

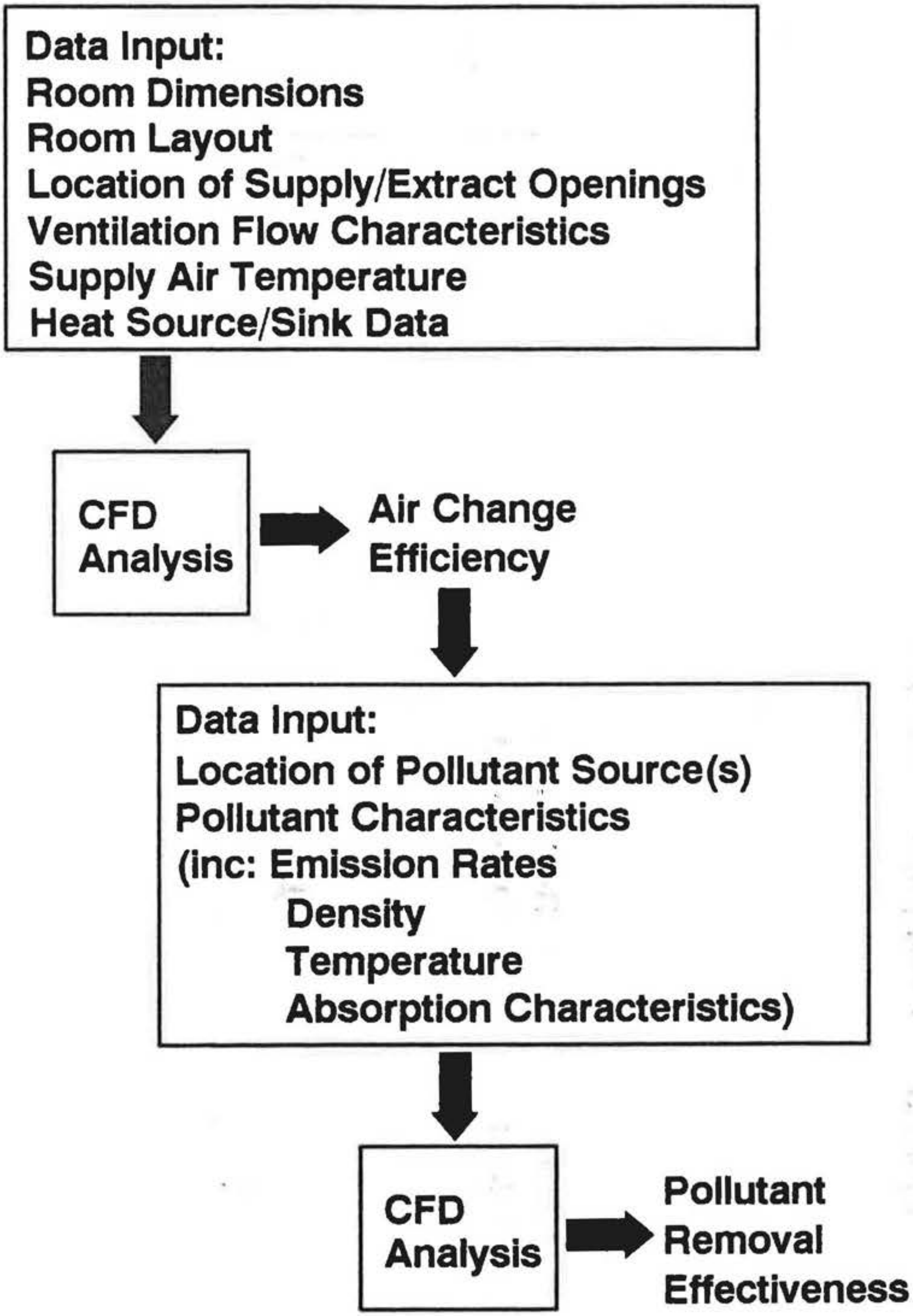

Figure 3 Example 1 - Uniform Mixing

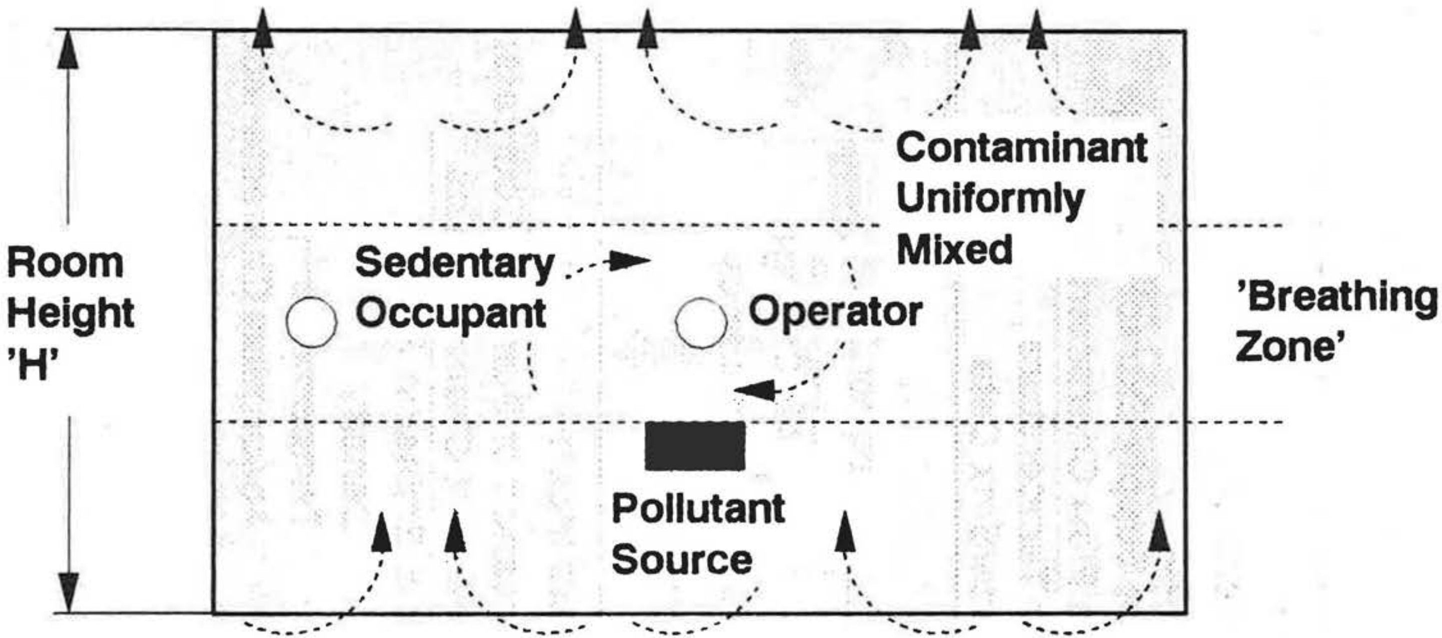

Figure 4 Example 2 - Piston Flow

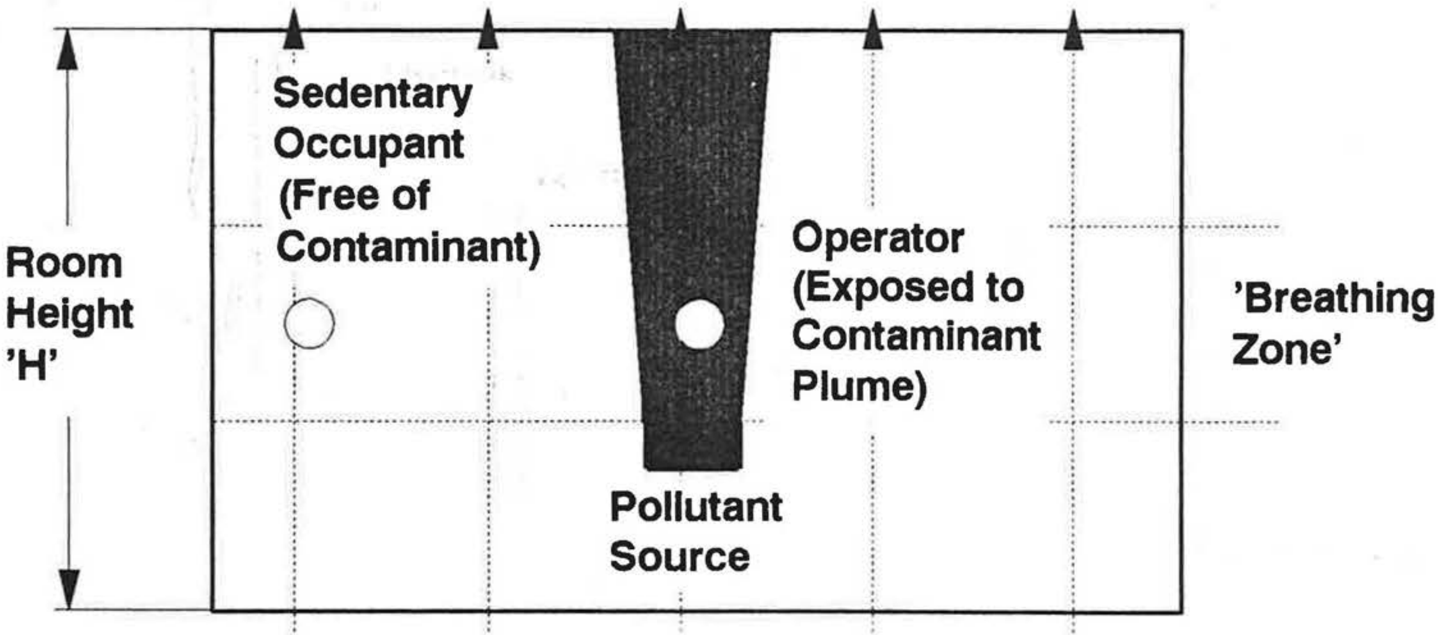

Figure 5   Example 3 - View of Room Layout

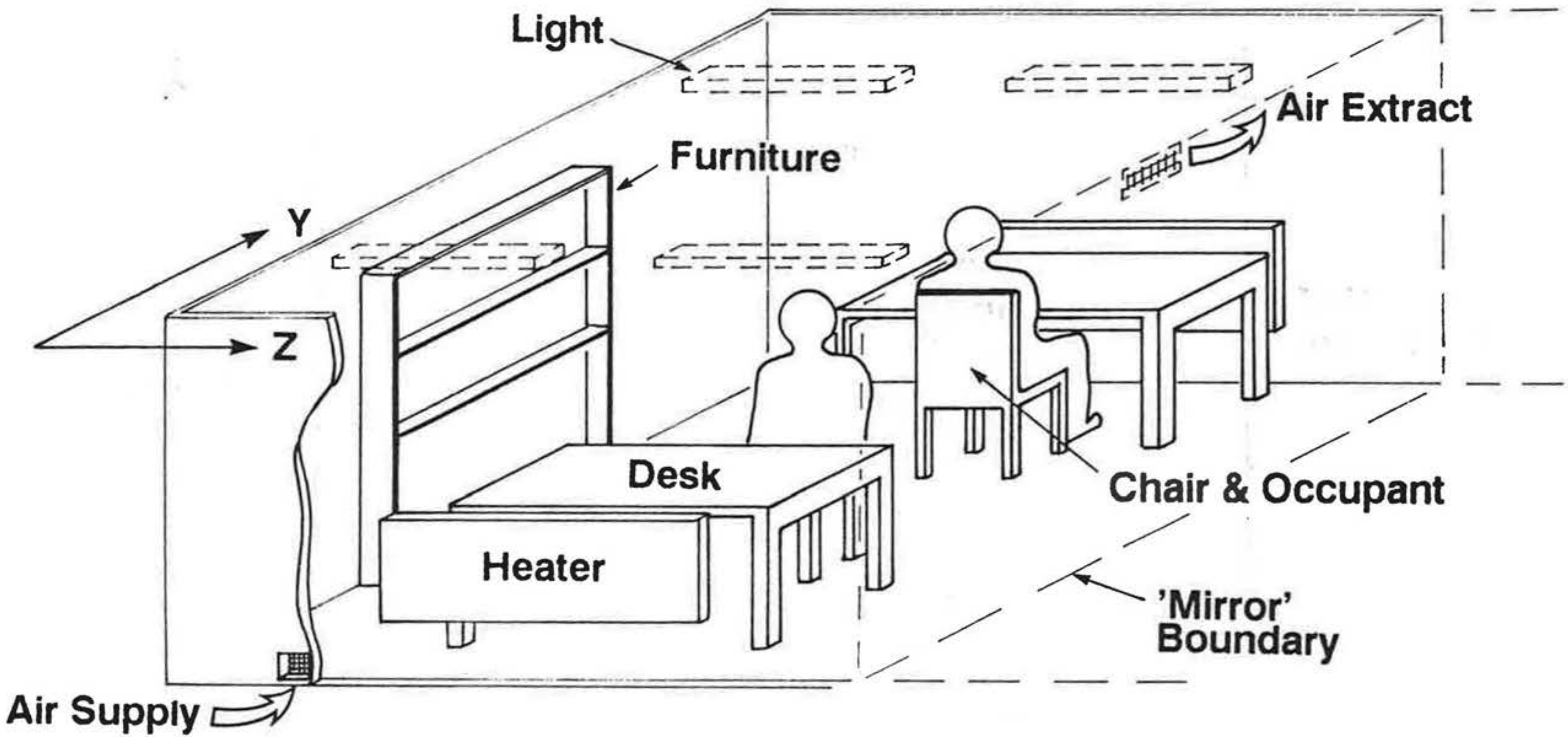

Figure 6 Predicted Pollutant Distribution

CO_2 Normalised to Extract Level