Measurement of Ventilation Efficiency for Indoor Air Quality in Office Buildings using Carbon Dioxide as a Tracer Gas

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By the way, said Candide, *do you agree with what they say in that big book the captain has, that the earth was originally all sea?*

I no more believe it, said Martin, *than I believe all the other delirious ravings that are published from time to time.*

But what was this world created for? said Candide. *To drive us mad,* replied Martin.

(Voltaire, Candide, 18th century)

Apprendre c'est créer

(Jean Piaget, 19th century)

...in the quiet & still air of delightful studies...

(marking engraved on the Redpath library, McGill University)

ABSTRACT

The work describes the results obtained following the development and testing of a new device used to measure ventilation efficiency for indoor air quality (IAQ) in office buildings. The method uses concentration data obtained by the repeated injection of CO_2 used as a tracer gas simulating human respiration. The device measures the efficiency of the ventilation in reducing and evacuating pollutants. Ventilation efficiency was measured in a test chamber and was demonstrated in an office building. The method was tested to determine if it responded well to the effect of air flows, air velocities, air temperatures, number of diffusers and room temperatures. Results compared well with the theoretical predictions obtained from a two-chamber compartment model and could be predicted using simple regression models (r=0.85). The work concludes that the new method can be used to measure ventilation efficiency and a chart is proposed for using the method with respect to recommended outdoor air flow rates in an office.

RÉSUMÉ

Le travail présenté fait état des résultats obtenus suite au développement et à l'essai d'un nouvel appareil servant à mesurer l'efficacité de ventilation pour la qualité de l'air intérieur (QAI) dans les édifices à bureaux. L'appareil de mesure évalue l'efficacité de ventilation à enlever les polluants à l'aide d'une méthode simulant la respiration humaine avec des injections répétées d'un gaz traceur, le dioxyde de carbone (CO_2). L'efficacité a été mesurée en chambre contrôlée et dans un édifice occupé. Les essais montrent l'effet des débits d'air, de la vitesse de l'air, du nombre de diffuseurs et des températures sur l'efficacité et décrivent la précision de la méthode. Les résultats obtenus sont semblables à ceux des méthodes existantes et se comparent bien avec les prévisions théoriques obtenues avec modèle à deux compartiments ou par des modèles de régression linéaire (r=0.85). Le travail conclut que la nouvelle méthode est utilisable pour mesurer l'efficacité de ventilation avec une charte de calibration permettant d'évaluer l'efficacité d'un diffuseur en rapport avec les recommandations d'air neuf dans un local de travail de bureaux.

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NOMENCLATURE

ach:	air change per hour
ac:	air-conditioning
ADPI:	air diffusion performance index
CO_2:	carbon dioxide
C_e:	room exhaust concentration
C_i:	room concentration at a point i
$C_{m,avg}$:	arithmetic average of measured CO_2 concentration
$C_{m,o}$:	background measured CO_2 concentration
$C_{m,sum}$:	summation average of CO_2 concentrations
C_{m1}:	initial measured CO_2 concentration
C_{m2}:	final measured CO_2 concentration
$C_{m,max}$:	maximum measured CO_2 concentration
C_o:	outdoor concentration
ε_a:	air exchange efficiency
ε_c:	pollutant removal effectiveness
ε_{cm}:	measured pollutant removal effectiveness
$\varepsilon_{cm,avg}$:	ε_{cm} based on $C_{m,avg}$ ($=\varepsilon_{cm}$)
$\varepsilon_{cm,max}$:	ε_{cm} based on $C_{m,max}$
$\varepsilon_{cm,sum}$:	ε_{cm} based on $C_{m,sum}$
F:	source of pollutant
f:	function between parameters
IAQ:	indoor air quality
K:	constant

k:	linear regression constants
N_2O:	nitrous oxide
ppb:	parts per billion
ppm:	parts per million
q:	outdoor air flow rate
q_{diff}:	diffuser flow rate
$q_{diffuser}$:	diffuser flow rate
r:	coefficent of linear corellation
rh:	relative humidity
RH:	relative humidity
SF_6:	sulphur hexafluoride
<t>:	room average-of-air
T_a:	air temperature
T_{air}:	air temperature
T_{ceil}:	ceiling temperature
T_{floor}:	floor temperature
τ_n:	nominal time constant
T_{rad}:	radiant temperature
T_{room}:	room temperatures
T_s:	supply temperature
T_{wall}:	wall temperature
T_{walls}:	wall temperatures
VAV:	variable air volume
VE:	ventilation efficiency
VOC's:	volatile organic compounds
V_a:	air velocity

1. INTRODUCTION

Concern for indoor air quality (IAQ) has grown over the past decades as new techniques have been developed to save and conserve the energy required for office building ventilation. Ventilation is now a vital component to improve IAQ in buildings that have become tighter and where modern materials have introduced new and more diverse sources of pollutants. Because ventilation in office buildings is now expected to maintain a much better balance between energy usage and human health and comfort, research efforts in IAQ have been devoted to the study of the performance or the efficiency of ventilation systems in achieving IAQ. Within this framework, the purpose of this investigation was focused on the development and the testing of a method for the measurement of ventilation efficiency (VE) in office buildings for IAQ.

VE is a relatively new concept in the field of IAQ and it describes the ability of a ventilation system to distribute air (ε_a) and dilute pollutants (ε_c) in a room. However, since VE is still a new concept there is not a single device that is currently able to measure VE in conditions of occupancy normally encountered in office buildings. Because it affects both IAQ and energy consumption, the knowledge of VE is a key to reduce IAQ complaints while taking into account the costs of ventilating for IAQ.

Since it evaluates outdoor air quantities and contaminant concentrations, VE is one of the important tools capable of determining the impact of these two parameters and to avoid cases of building related illness (BRI) or the occurence of the so-called sick building syndrome (SBS). VE can have a significant effect on the well-being of people working in office buildings if it is assumed that IAQ related symptoms such as the sensation of lack of air may be related to low VE. VE has also a significant impact on energy consumption required to ventilate spaces since low VE is a sign of poorly designed and inefficient ventilation. Energy savings obtained through an improved VE can be used to enhance ventilation and thermal comfort and other aspects of IAQ. Although VE is an important concept for IAQ and energy conservation, the application of this concept in practice continues to evolve as more and more studies are performed.

In the past fifteen years, numerous methods have been developed to measure VE based on the experience acquired in laboratories and in the field with tracer gas techniques. Compared to other methods based on air velocity and air temperature measurements, tracer gas techniques provide a faster and more accurate way of measuring directly air movements and air flow rates in closed-circuit chambers. Over the years, descriptions of methods to measure VE based on tracer gases have become more accessible and have been studied and tested more extensively. Nevertheless, there are still severe restrictions that prevent the adoption of a standard method to measure VE despite the efforts of researchers and agencies involved with the issue.

To date, the methods developed in control chambers for measuring VE suffer from a series of limitations that have prevented them to be widely used in the field. This is mainly due to the fact that field conditions observed in practice are far more unpredictable and complicated than test chamber conditions. One tactic to circumvent this limitation has been been to convert buildings into elaborate test chambers to measure VE at night when buildings can be controlled at will and the occupants have left. Researchers can then resort to elaborate test protocols that would normally disturb the occupants during the day. For example, potentially toxic or anaesthetic tracer gases are used (e.g.: refrigerant R-12, sulphur hexafluoride, nitrous oxide), bulky and invasive instrumentation is deployed and ventilation is altered. Even if some methods have overcome a few of these limitations, the most important challenge in the problem of measuring VE in the field has remained the question of defining the concept in such a way that that the theory or the models developed in the test chambers are applicable in practice.

The limitations described above were taken into consideration and used as in the development of the proposed method. It was decided that the method had to be developed, as far as possible, based on accepted concepts already applied and tested. The method, had to avoid disturbing ventilation and office workers to be used during working hours. Finally, in addition to these constraints, it was felt that the method should be simple enough to be applied by practitioners involved with IAQ without compromising the accuracy and the validity of the results.

To develop the VE method proposed within this scope, it was necessary to retrace the steps followed by other researchers in the development of their methods. The subject had to be understood extensively at first using a literature review to put the concept of VE in its proper perspective. Second, based on this review, a solution or method for the measurement of VE in office buildings was proposed (ε_{cm}) and developed. A test chamber and a VE measurement system were then constructed to study the response of the method to the parameters expected to be critical in the field. Experimental results for the chamber studies were obtained as well as for a demonstration in the field. These results were analysed in order to finally conclude on whether the ε_{cm} method can be used for the measurement of VE in office buildings.

2. LITERATURE REVIEW

A building can be seen as a tool used to create a barrier between an exterior or natural environment and an interior or artificial environment. In practice, this barrier should be able of preventing outside elements from disturbing the comfort and the health of the occupants living or working inside. This means that, as far as possible, the barrier should be selective enough to allow only the right factors to enter. Over the years the necessity to define these factors and find ways to satisfy this function has been associated with the developement of IAQ as a science.

Because there are many different ways to achieve IAQ in buildings, engineers and architects have long debated on the best possible approach to design for IAQ. Overall, the debate over the question can be divided according to the type of control that is expected from a building. On one hand, a passive or "natural" approach favours the creation of buildings with a restricted amount of mechanical equipment. This means, among other things, that buildings are ventilated by infiltration of outside air through the building envelope or through the opening of windows and doors by the occupants. For these buildings, only a heating system will be necessary to raise indoor temperatures in winter and the draft or air currents should provide a sensation of freshness to the air in the summer.

The other approach to IAQ involves the use of active means in the form of a ventilation systems used to perform the same functions. Ventilation systems are used to supply and remove air from the occupied zones. They can also be fitted with devices to filter the air and condition it to the right temperature and humidity for IAQ. Each approach has its advantage and may be used seperately or in combination to suit different climates and different types of weather.

Irrespective of the strategy used in designing a building, the final result is generally agreed to be the satisfaction of the correct conditions for IAQ for people. This goal can be achieved at different costs and must be achieved with as few compromises as possible. In the remaining part of this chapter, the study of the question of IAQ is introduced along with the term VE that is defined as one of the tools used as a mean to achieve this goal. These two concepts will form the basis for the methodology developed to test and evaluate the proposed method to measure VE in actual buildings that is developed in the reminder of this thesis.

2.1. Indoor air quality

The study of IAQ is a science that deals with the health and comfort of people living and working in enclosed spaces. An historical review on the subject indicates that IAQ was already a concern as far back as 400 B.C. when the Greeks and the Romans questioned the effect of air pollution on people who lived in crowded cities or people working in mines [1]⁺. IAQ became an important concern again in the 1700s as these same conditions affected the people engaged in the industrial revolution who moved from a primary agricultural society to a more industrialised and city-based society [2].

In England and later throughout the world, these changes in the working and living conditions of people fostered the development of new sciences necessary to deal with IAQ and industrial diseases in general. For example, epidemiology started to be applied to study the unusually high incidences of scrotal cancer caused by chimney fumes (Pott, 1778) and was also used to study the effect of air pollution on the health of people living in densily occupied rooms [3]. Later, industrial hygiene techniques soon indicated that CO_2 exhaled by people could be an important factor related IAQ and could cause the sensation of stale air [4]. Already by the mid 1850s IAQ studies were performed in a way that is similar to today with measurements of the effect of CO_2, air flows, temperatures and humidity on IAQ in schools [4].

⁺ Numbers in square brackets are references at the end of this thesis

It was not until the 1930s that IAQ took a new turn and became a distinct science as part of the workforce went from industry into an expanding commercial sector that caused an increase in the number of people working in office buildings [5]. Even though the first skyscraper was built in 1884 in the United-States [6], it was not until the 1930s that refrigerants (e.g. : CO_2, ammonia and sulphur dioxide) allowed the use of air-conditioning (ac) in closed buildings and was applied in hospitals, theatres and in the food industry [5].

In the 1930s, the first systematic attempt to define IAQ in general was made by Yaglou and colleagues following the study of body odour in relation to ventilation rates [7]. Their work enabled them to define IAQ in terms of the correct combination of factors to insure that odours do not dissatisfy occupants and air is felt as fresh and pleasant when entering a room. Along with ventilation rates and odours, these factors included temperature, humidity and drafts (air movements). They also mentioned the effect of recirculating air on the sensation of "freshness" by pointing out that a certain portion of outdoor air was needed to be recirculated to augment the amount of total air (outdoor and recirculated air) distributed in a room and to control temperatures inside [7]. These investigations showed the effect of IAQ on comfort (e.g. : odours and temperature) but did not consider IAQ as an important health problem.

The period between the 1930s and 1960s was marked by the development of new technologies that allowed the widespread use of ac in all sectors of activity [5]. The main reason for this evolution was the new technological improvements in ac that included the development of new refrigerants (e.g. : R-113, R-114, R-11, R-12) and elaborate ventilation systems in the 1950s [5]. These systems included induction systems (window units), double-duct systems (one cold and one warm air stream are mixed to obtain the correct room temperature and air volumes), terminal reheat (cool air is reheated by small electrical elements located in the end of the ducts) and variable air volume systems or VAV (air volumes are varied using a variable speed fan or a control box with a damper). This period was marked by the transformation of ac from "a luxury to a necessity" and systems were used for comfort without much concern for energy resources that seemed abundant and inexhaustible at the time [5].

It is in the 1970s that IAQ took a new turn because of the severe energy crises that forced the need for "super-efficient" buildings [5]. At this point, the ventilation and ac systems developed earlier became heavy drains on the economy and the industry responded by developing a series of measures to improve these systems and develop new and more performant alternatives. These alternatives included mainly the reduction of outdoor air volumes and better control of the systems for ventilation and ac [5]. Also, systems were shut off during the night and improvements were made on the mechanical efficiency (energy spent over work produced) of the systems [5].

As a result of the changes occurring in the ventilation systems in the 1970s, in the 1980s and 1990s IAQ became a health concern as new risk factors for people living in closed spaces were identified [8 to 19]. Researchers have provided elements to be added to the list of potential risks for IAQ and these include : odours [20 to 28], organic and inorganic dust [29], radon (radioactive gas emanating from rocks in building foundations) [30,31], formaldehyde (used in building materials such as insulation and glue) [32,33], volatile organic compounds (from people and machines such as photocopiers) [34 to 40], bacteria and virus and moulds (causing infections, hypersensitivity, allergic reactions) [41,42], gases such as CO_2 (from people and combustion equipments), carbon monoxide and nitrous oxide (from combustion equipments) and ozone (from photocopiers and outside air) [43 to 46].

The combination of the potential risk factors for IAQ has led to the definition of the term "Sick Building Syndrome" (SBS) by authorities and was recognised in the public in general. The World Health Organisation defines SBS as a set of symptoms that comprises eye, nose and throat irritation, cough and high frequency of airway infections, hoarseness, wheezing, itching, nausea and dizziness [47]. In buildings afflicted by SBS people usually get better a short period of time after they have left the premises. This is different from Building Related Illness (BRI) that is caused by a identifiable factor such as a microbial contaminant causing a clinical symptom (asthma, hypersensitivity pneumonitis, allergic rhinitis, pontiac fever and Legionnaires disease) and usually involves a prolonged recovery time after the building is left [47].

2.2. Standards and guidelines for air quality in office buildings

The result of the research and the development efforts made in the science of IAQ has finally lead to the creation of standards and guidelines for IAQ in today's office buildings. These standards developed since the begining of the 1990s provide the criteria that are considered as state of the art in the fields related to IAQ such as health sciences and engineering. Although they may vary in some aspects, these guides can be used as the basis for the current definition of IAQ as well as the approach to ventilate for IAQ in office buildings.

In North America and in Europe, several agencies have published standards and guidelines for ventilation and air quality. In Canada, Exposure Guidelines for Residential Air Quality [48] are used for the residential sector and American recommendations are followed for office buildings. In the United States, the American Society of Heating, Refrigerating and Air-Conditioning Engineers [49] publishes a standard, the ASHRAE Standard 62-89 that is entitled, 'Ventilation for Acceptable Indoor Air Quality' endorsed by the American National Standard Institute (ANSI). In Europe, one of the main references for ventilation and indoor air quality is the 'Guidelines for Ventilation Requirements in Buildings' published by the European Concerted Action [50].

Each of the above standard references has a different definition of IAQ in office buildings. For ASHRAE [49], acceptable indoor air quality is defined as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction." The Canadian definition [48] states that biological, physical and chemical agents should be controlled to insure a negligible risk to the health and safety of the occupants. The European recommendations define air quality as the control of pollutants to insure negligible health risks and state that the air should be perceived as "fresh and pleasant" by the occupants [50].

The ASHRAE standard [49] prescribes two approaches to achieve air quality in office buildings : a) control contaminant levels below a certain prescribed level for health and comfort and, b) provide a minimum outdoor air supply rate based on the number of occupants and the type of activities performed.

These two options have a different impact on IAQ depending on the choice of option that is selected by building designers. If ventilation system designers select the first option, then the concentrations of pollutants must be measured or controlled inside buildings to insure that their levels are below recommended values. The designers must show that they can achieve this objective under normal conditions of operation. This is usually a difficult approach and more often, designers work using the second option. If the second option is selected, designers use the minimum outdoor air flow values prescribed by ASHRAE. These outdoor air ventilation rates are meant to maintain carbon dioxide (CO_2) concentrations below 1000 ppm based on a typical number of occupants in a zone [49]. The amount of outdoor air recommended is 10 L/s per person but varies according to the type of workplace [49].

2.3. Ventilation efficiency

Research has shown that IAQ involves mainly three components (humans, fresh air and pollutants), and it is normal to seek a method to measure each of these components to evaluate IAQ in a space or what can also be called the VE of a space. The different studies on VE performed over the past fifteen years [51 to 104] have yielded important findings on the question;however, there is still a confusion concerning the terms used to define the concept [78,100].

The main cause of the confusion has been the wide variety of terms used to express VE by different researchers [78,100]. For example, in a review on the subject by Liddament in 1987 [78], VE was alternatively expressed as "relative ventilation efficiency", "overall relative efficiency", "absolute ventilation efficiency", "transient relative ventilation efficiency", " relative air diffusion efficiency", "air exchange efficiency" and "ventilation effectiveness"[78]. All these definitions dealt with the interaction between outdoor air, human perception and pollutant sources and were applied using tracer gas techniques. In a second review in 1993, Liddament had narrowed the field of VE to "outdoor air distribution" and "pollutant removal" only [52]. Although the human component of VE was excluded in these terms that are related mostly to the description of air movements, the basic idea was that human perception is satisfied when these two functions are performed correctly.

Analysis (see figure 2.1) of the most recent literature indicates that VE can be categorized further as: VE for human perception of odours, ε_χ,[22, 23] VE for outdoor air distribution, ε_a [53 to 69] and VE for pollutant removal effectiveness or ε_c. [70 to 95]. Thermal comfort can also be dealt using the concept of VE but the application of VE to thermal comfort is not performed using tracer gas techiques.

For all three definitions, VE is defined by comparing model predictions (numerical or physiological) with results obtained under field conditions [100]. Most of the theoretical models used so far have been borrowed from disciplines such as chemistry or from fluid flow dynamics and these models were originally intended to study flows in chemical reactors or to analyse the flow of air and water in channels [51 to 55].

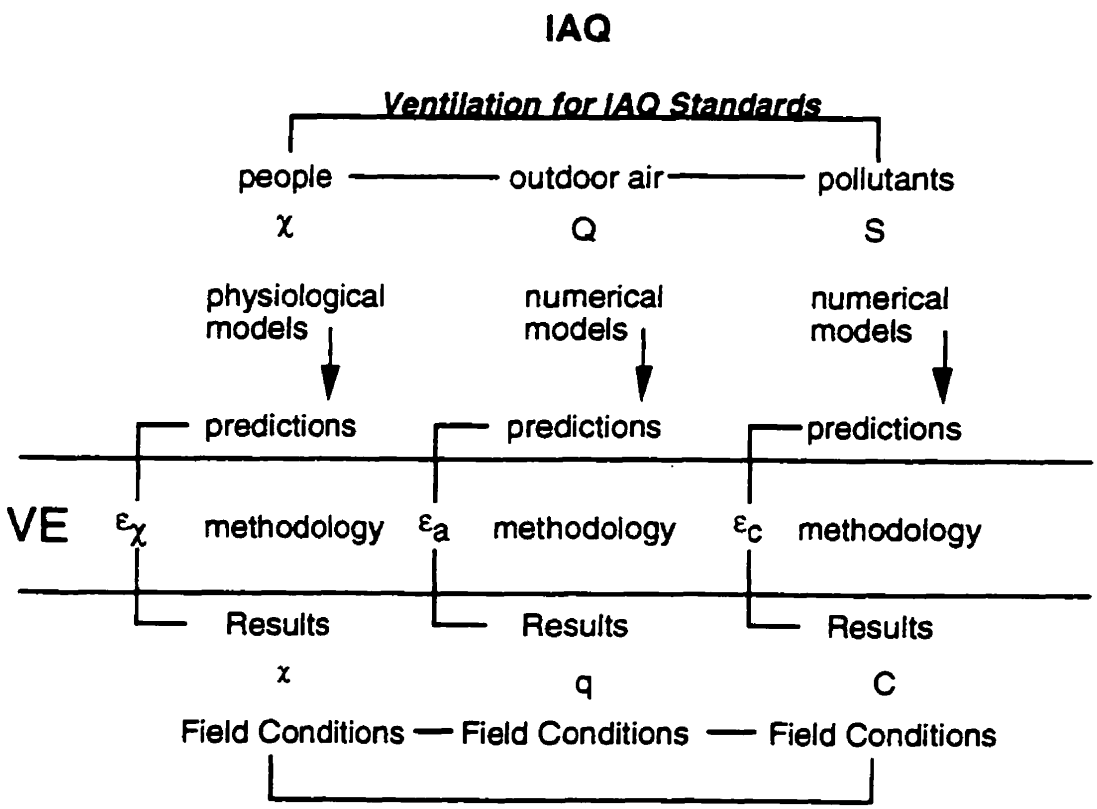


Figure 2.1: Ventilation efficiency concept used for the evaluation of ventilation for IAQ in office buildings

The definition of ε_χ, is obtained by comparing the results from physiological models to predict human's response to odours or pollutants (e.g.: VOC's, CO_2) with results from tests performed in controlled chambers to verify the actual percentage of people dissatisfied by certain selected odour levels [24,25].

The definitions of ε_a and ε_c compare the results from air flow modelling predictions to actual or observed airflows measured in office buildings and are mostly physical models developed from chamber studies [78,88,100]. The models borrowed from other fields were modified to adapt to building conditions [55].

After they were modified by testing in test chambers, different methodologies were proposed to verify the predictions of the models in actual field conditions. Up to now, the methods used for ε_a and ε_c have mostly involved the injection of tracer gases to label the air in a space [51 to 104]. The methods for ε_χ have not evolved past the modelling or design stage [94]. Even though it is assumed that there is a relation between results obtained using ε_a, ε_c or ε_χ there have been only a few recent attempts to establish this relationship experimentally or theoretically.

2.4. Air exchange efficiency (ε_a)

2.4.1. The age-of-air concept

The "age-of-air" is a concept similar to the concept used in demographics to describe the average age of a human population [97]. Similar to a human population, the gas molecules that are present in a room at a given instant can be assigned an age. This age is assigned by first letting the air molecules that are entering the room be the "youngest" molecules and then letting the other molecules have progressively "older" ages until they are evacuated or "die" (see Figure 2.2) [97]. Assuming that the air in a room is a uniform mixture of different gases (e.g.: oxygen, nitrogen, CO_2), the average age of all the molecules in the room is called the "average age of the air" for the room and is identified as $<\tau>$ [97].

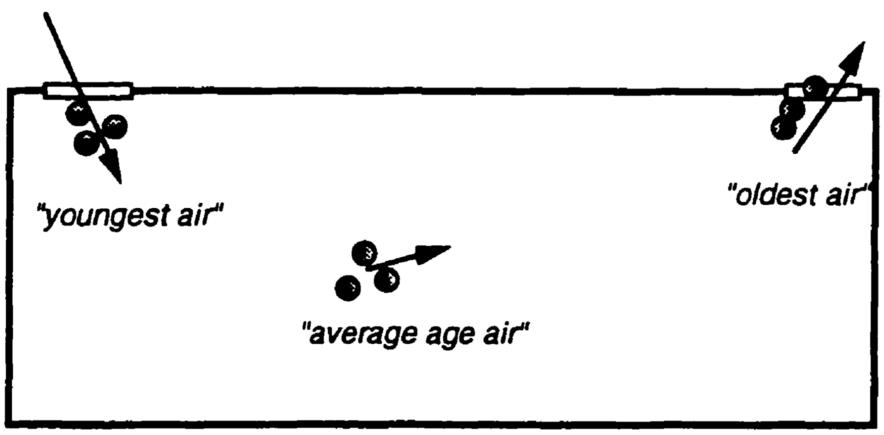


Figure 2.2: Age-of-air concept

2.4.2. Definition of air exchange efficiency

The definition of air exchange efficiency can be formulated by stating that the goal or objective of the ventilation in a room is to reduce <t> to a minimum value. According to this definition, if <t> is low, then the ventilation is efficient and the air leaves the room rapidly. On the contrary, if <t> is high, then the ventilation is inefficient and the air stays longer in the room.

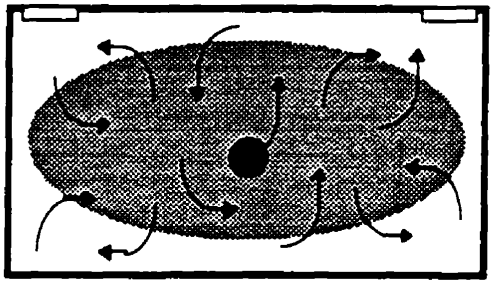
According to this definition, the minimum <t> or the optimum ventilation time has to be defined with respect to a standard reference value. In theory, <t> could be reduced to a value near zero if enough air is delivered in a room. However, this is not practical since the air flow rate would be too high for human comfort. The minimum value for <t> must therefore be established on a different criterion than time alone.

The criterion proposed by Sanberg [53,54,56,62,67,68,73,75,97] and by others [100], consists in comparing the airflow rates with a theoretical estimate of the best or optimum <t> for a room. This minimum, that is represented by τ_n, is also referred as the nominal time constant of a room. The value of τ_n is obtained using numerical expressions based on models used to predict the time for a volume of air to ventilate a room.

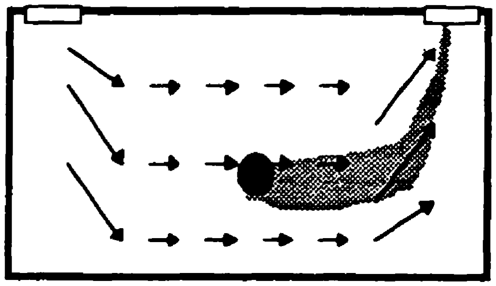
As shown in Figure 2.3, for analysis purposes, the air movements or airflows in a room can be assumed to follow three types of behaviour : a) piston flow, b) mixing flow and, c) by-pass or short-circuiting flow [100]. The airflow patterns created are shown with arrows and the resulting effect of these flows on pollutants is shown in greyed areas for a point source located in the centre.

As shown, piston flow is an ideal flow where all the molecules of air go from one end of the space (age zero) directly to the other side to be evacuated (maximum age). This is a very efficient flow for the evacuation of pollutants but it may cause problems if someone is in the path between the source and the exhaust of the ventilation. Ideal or perfect mixing flow (definitions vary [97]) is a flow where all the air in the room has the same age (average age) and the room is ventilated at the same rate in each portion or zone in the room. For this type of flow, the pollutant source has less chances of being in high concentrations in the path of the flow, but everyone in the room is eventually exposed to the pollutant since it is distributed everywhere.

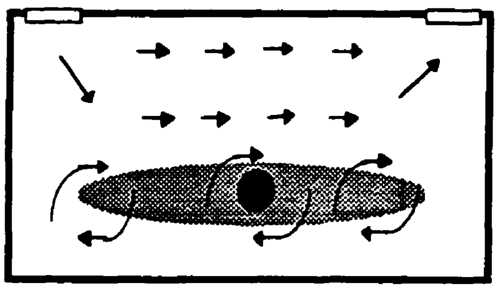
Finally, short-circuiting flow is the flow that is expected to be observed in an actual room. This is the worst case where the air is not distributed in certain parts of the room because of obstacles (e.g.: room partitions, furniture) or other factors (e.g.: temperature gradients, local exhausts) affecting a smooth and efficient flow of the air.



a) perfect mixing



b) piston flow



c) short circuit flow

● : point source of pollutant

: distribution of the pollutant in the room

Figure 2.3: Theoretical flows used for age-of-air predictions

Using the perfect mixing flow model, and assuming that the room conditions (temperatures, airflows, room layout and volume) do not change (steady-state) and that there are no other sources of air (e.g.: infiltration, local exhausts), then, the theoretical age for the air in the room can be calculated using the following equation for perfect mixing flow [97,100,102]:

$$\tau_n = \frac{V}{q} = \frac{1}{n} \qquad (1)$$

where : τ_n is the shortest time spent in the room by the air (minutes),
q is the outdoor air flow rate through the room,
V is the volume of the room (m^3), and,
n is the air change rate (air changes per hour).

This expression states that the time required for the air to ventilate a space under fully mixed conditions is equal to the volume of the room (m^3) divided by the q (L/s) through the room. The average time spent by the air, τ_n, is expected to decrease as the flow rate of air going through the room increases [100]. The air change rate, which is the reciprocal of τ_n, expresses the number of times the volume of the air is changed in an hour instead of the time spent by the air in the room. For piston-flow, τ_n can be shown to be equal to half of the value for fully mixed conditions and for short-circuiting, τ_n is greater than for both piston and fully mixed conditions.

Based on these flow predictions, two definitions or expressions of ε_a are obtained. A first definition of ε_a, (see Figure 2.4) is obtained if the room conditions are compared to what would be obtained using piston-type of flow [64]:

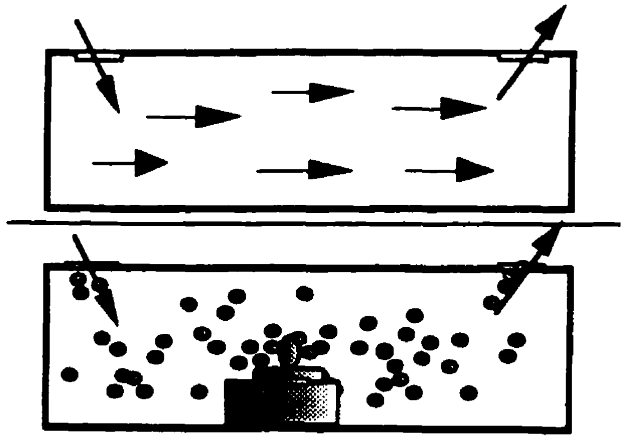
$$\varepsilon a1 = \frac{\tau n}{2<\tau>} \qquad (1.1)$$

Using this formula, for a piston type of airflow, the efficiency will be 100%; for room conditions close to perfect mixing, the efficiency is 50%; and for short-circuiting conditions (air from diffusers is exhausted before it can reach the occupants), the efficiency is inferior to 50%. According to the latest ASHRAE proposal however, the definition of ε_a is obtained by comparing the $<\tau>$ to perfect mixing instead of piston flow [97,100,102]:

$$\varepsilon a2 = \frac{\tau n}{<\tau>} = 2\varepsilon a1 \qquad (1.2)$$

Using ε_{a2}, for piston type of flow, the efficiency will be 200%, for room conditions close to perfect mixing, the efficiency is 100% and, for short-circuiting conditions, the efficiency is inferior to 100%.

$$\varepsilon_{a1} = \frac{\tau_n}{2<\tau_n>} = \frac{\text{piston-flow}}{\textit{actual}} = \quad (1.1)$$



$$\varepsilon_{a2} = \frac{\tau_n}{<\tau_n>} = \frac{\text{perfect mixing}}{\textit{actual}} = \quad (1.2)$$

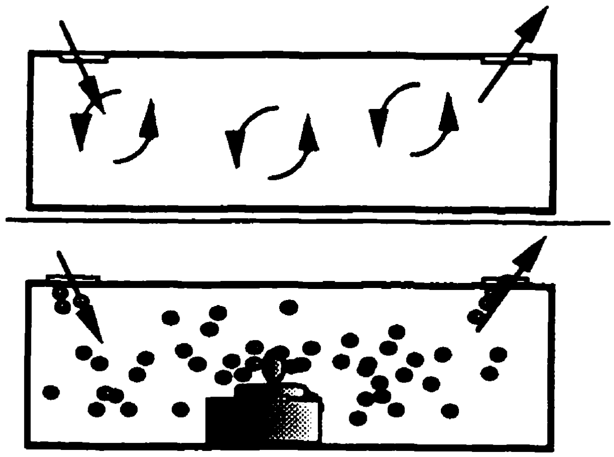


Figure 2.4: Definitions of ε_a using comparison of actual flow with predictions based on assuming piston (ε_{a1}) or perfect mixing flows (ε_{a2})

To measure the actual value of $<\tau>$, a tracer gas is injected in the room while there are fans mixing the air [105 to 111]. If the gas is mixed within a relatively high degree of uniformity by the fans, then the values of the concentrations in the room will not vary by more than a few percent relative to a mean value. Under these conditions, the assumption of "perfect mixing" will be verified and, it can be shown that the concentration decay of the gas in the air will follow the relationship [88]:

$$C(t) = C'e^{-n't} \qquad (1.3)$$

where:	C(t)	is the tracer gas concentration in time,
	C'	is the initial tracer gas concentration,
	n'	is the air change rate measured (ach).

Because there are fans mixing the air in the room, these are conditions close to the assumption of perfect mixing and the value of n' can be substituted for n into formula 1 to obtain the value of τ_n for the room.

One of the tracer gas methods used to measure $<\tau>$ involves the uniform injection of the tracer gas followed by the collection of a continuous sample of this gas in a sampling media (e.g.: canister, tedlar bag) [102]. At the end of the decay of the gas or when the gas has disappeared from the space, the sample is retrieved and the concentration of the gas in the sampling media is measured.

The value of <t> can then be calculated using the following formula [102]:

$$<\tau>= \frac{d' \, Cs}{Cs,o} \qquad (1.4)$$

where: d' is the sampling duration,

C_s is the final sample concentration,

$C_{s,o}$ is the initial sample concentrations.

This value of $<\tau>$ is inserted in formulas 1.2 or 1.3 to calculate ε_a for the room studied. The sampling method can be substituted by other methods and these methods require different injection and sampling schemes [102].

The main limitation of the definition of ε_a using the age-of-air concept is that it is a relative index. The value of ε_a is not an absolute measure of the efficiency of ventilation to distribute outdoor air because each room in a building has a different τ_n. Consequently, the theoretical maximum predicted by τ_n, is specific to the room size and this means that for the same percentage of efficiency, there is more outdoor air distributed in a bigger room than in a smaller one. Since IAQ depends on this amount of outdoor air, the values of ε_a may be misleading and can not be interpreted directly to assert that, if a space is ventilated efficiently then the people will be satisfied and the contaminants are removed properly.

2.5. Pollutant removal effectiveness (ε_c)

2.5.1. Concept of pollutant removal

Because ε_c evaluates the control of air pollutant by a ventilation system instead of the overall distribution of outdoor air, the definition of this parameter can not be approached by the age-of-air concept. In the age-of-air approach, it was possible to use the simple assumptions of "perfect-mixing", "piston" or "short-circuit" flows because ε_a was defined for the outdoor air distribution over the whole volume of the room. Contrary to outdoor air, most pollutants are not distributed uniformly in a room and they are generated inside of a specific zone. Therefore, the ability of the ventilation system to control a given source by removing or diluting this source from the space, or the ε_c of the room, depends highly on the location and the type of sources [88,90].

The ε_c for the space is usually defined with respect to the concentrations reached by a given pollutant in a space [50,78,90,94,95,98,99,102 to 104]. Some of the pollutant sources of concern for IAQ are shown in Figure 2.5. These sources illustrate the different types of sources and their associated distribution patterns. In this example, a human source is acting as a point source (e.g.: CO_2, VOC's) located in the centre, while carpets, furniture and equipment sources are generated evenly or in more specific parts of the interior [88,90]. From this diagram, it is apparent that the definition of ε_c must be different for each of these sources and other compounds of concern for IAQ in office buildings [78,100]. However, since there exist similarities between the physical properties of the sources (e.g.: CO_2 and VOC's), some sources may be used as substitute for others [17]. Also, the type of distribution of the pollutants is usually grouped as being either a point source (e.g.: cigarette smoke) or a distributed source (e.g.: carpets) [17]. The definitions of the sources and their distribution patterns vary according to the authors and the particular conditions studied or simulated [78,100].

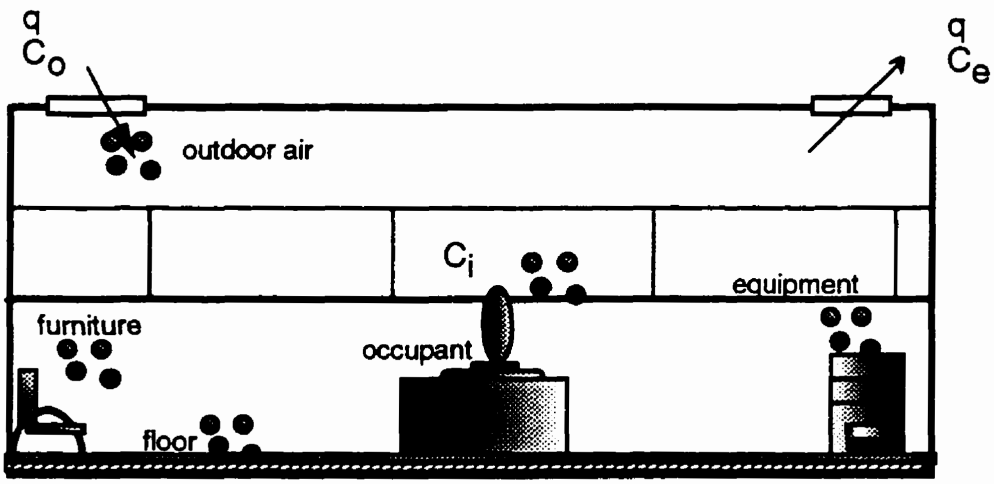


Figure 2.5: Example of sources of pollutants used to define ε_c

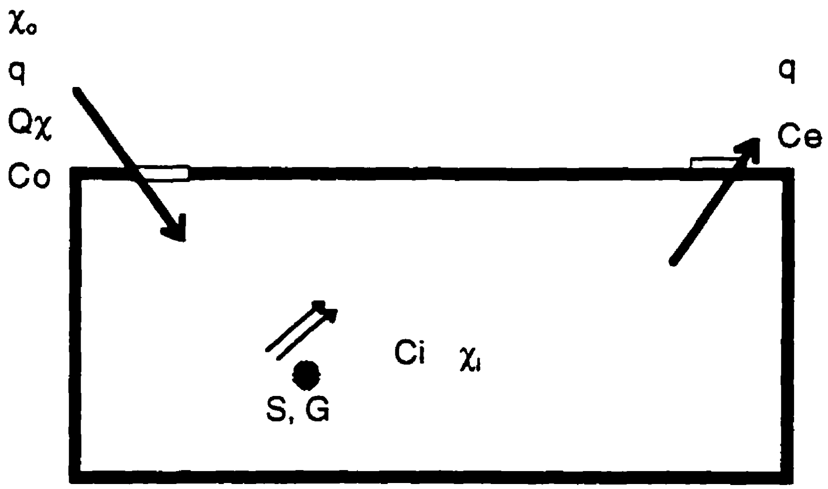
2.5.2. Definitions of pollutant removal effectiveness

Whereas ε_a was defined as the ratio of actual over predicted air change rates (or expected age-of-air), ε_c is defined by the ratio of observed pollutant concentrations over predicted room concentrations. In this case, it is assumed that the goal of the ventilation is to reduce concentration levels down to a theoretical minimum. In the literature, the definitions vary with respect to the minimum concentration that is to be used in the calculation of ε_c [78,88,90,100].

Figure 2.6 shows five of the definitions commonly proposed to measure or evaluate the ε_c of a space and the formulas used to calculate this parameter based on pollutant concentrations. Although some definitions have been omitted, most definitions that appear throughout the literature can be related to these basic definitions. Definitions 2.1 to 2.4 are definitions based on the maximum concentration of the pollutant source (or tracer gas) that would be obtained under a certain theoretical air flow distribution in the room. On the other hand, definition 2.5 deals with perceived concentrations of odours instead of concentrations of pollutants. Definition 2.5 can only be used for design calculations at present but, this definition may eventually be applied in the future if techniques to measure odours can be developed to measure them in the same way as pollutant concentrations.

The definitions of ε_c shown in Figure 2.6 can be divided according to two types of categories defined with respect to the theoretical value used for predicting the highest ε_c possible to achieve in a space. In the first category, the minimum concentration in the room is defined relative to the concentration in the exhaust air of the ventilation such as C_e in formula 2.1 [51] or with respect to both exhaust concentrations and outdoor air concentrations, C_o as it is the case definition in definition 2.2 [102]. These two types of ε_c can be referred as "concentration ratio" definitions since they only involve concentrations of pollutants. Definitions 2.3 to 2.5 are definitions that use the minimum concentrations that would be obtained if the pollutant were diluted under ideal flow conditions [87, 50]. These definitions can be referred as definitions based on pollutant source and ventilation rate to differentiate them from the first type of definition.

a) parameters involved in the definitions of ε_c



A: area of the room
S,G: source of pollutant
n: number of sources

Ci: room concentration of pollutant
Ce: exhaust concentration of pollutants
Co: outdoor concentration of pollutants
χ_i: desired indoor comfort level based on human perception

q: outdoor air flow rate
Qχ: design outdoor air flow rate

b) definitions of ε_c

No.	Method	Formula
2.1	room and exhaust concentrations [50,57,69]	$\varepsilon_{c1} = \frac{C_e}{C_i}$
2.2	room, exhaust and outdoor concentrations [88,90]	$\varepsilon_{c2} = \frac{(C_e - C_o)}{(Ci - C_o)}$
2.3	source emission rate, ventilation and room and outdoor concentrations [50,57,94]	$\varepsilon_{c3} = \frac{S}{q(Ci - C_o)}$
2.4	room concentration and source strength (k=constant)[99]	$\varepsilon_{c4} = \frac{kACi}{nG_o}$
2.5	source emission rate, outdoor ventilation rate and human perception [102]	$\varepsilon_{c5} = \frac{10}{Q\chi}\frac{G}{(\chi_i - \chi_o)}$

Figure 2.6: Definitions of ε_c based on pollutant concentrations, pollutant sources and ventilation

2.5.2.1. Definitions based on source strength and ventilation rate

Since pollutant sources are usually encountered in specific portions of a room, the approach that is adopted to predict the minimum concentration of a pollutant is to divide the space in smaller portions or compartments [116]. This approach is illustrated in Figure 2.7 where a point source and a diffused source are shown in a room with ventilation. How the volume in the room is divided depends on the accuracy that is desired from the model [116]. A one model compartment is a simple but fairly poor model because it only indicates how the air enters and leaves the room. More than three compartment models are usually better handled by computers because the number of equations required to solve for the flow of air through each of the small elements involves more extensive calculations [116]. For simple evaluation purposes, a two-compartment model would be a better choice between accuracy and simplicity compared to the other models [116].

Based on a two-compartment model, the following formula allows to calculate the maximum concentration reached by a pollutant inside of a space [49,110,116]:

$$Ci = Co + \frac{F}{q} \qquad (2)$$

where : C_i is the final pollutant concentration in the room,

C_o is the initial pollutant concentration in the room,

F is the pollutant generation rate, and,

q is the ventilation rate (outdoor air).

This formula forms the basis for definitions 2.3 to 2.5 shown in Figure 2.6. It states that the final concentration reached by a gas (or pollutant) in a room is equal to the initial concentration of this gas plus a factor based on the pollutant's generation rate divided by the outdoor air flow into the room. This formula also forms the basis for the formula used by ASHRAE to set the ventilation rate [49] in a room.

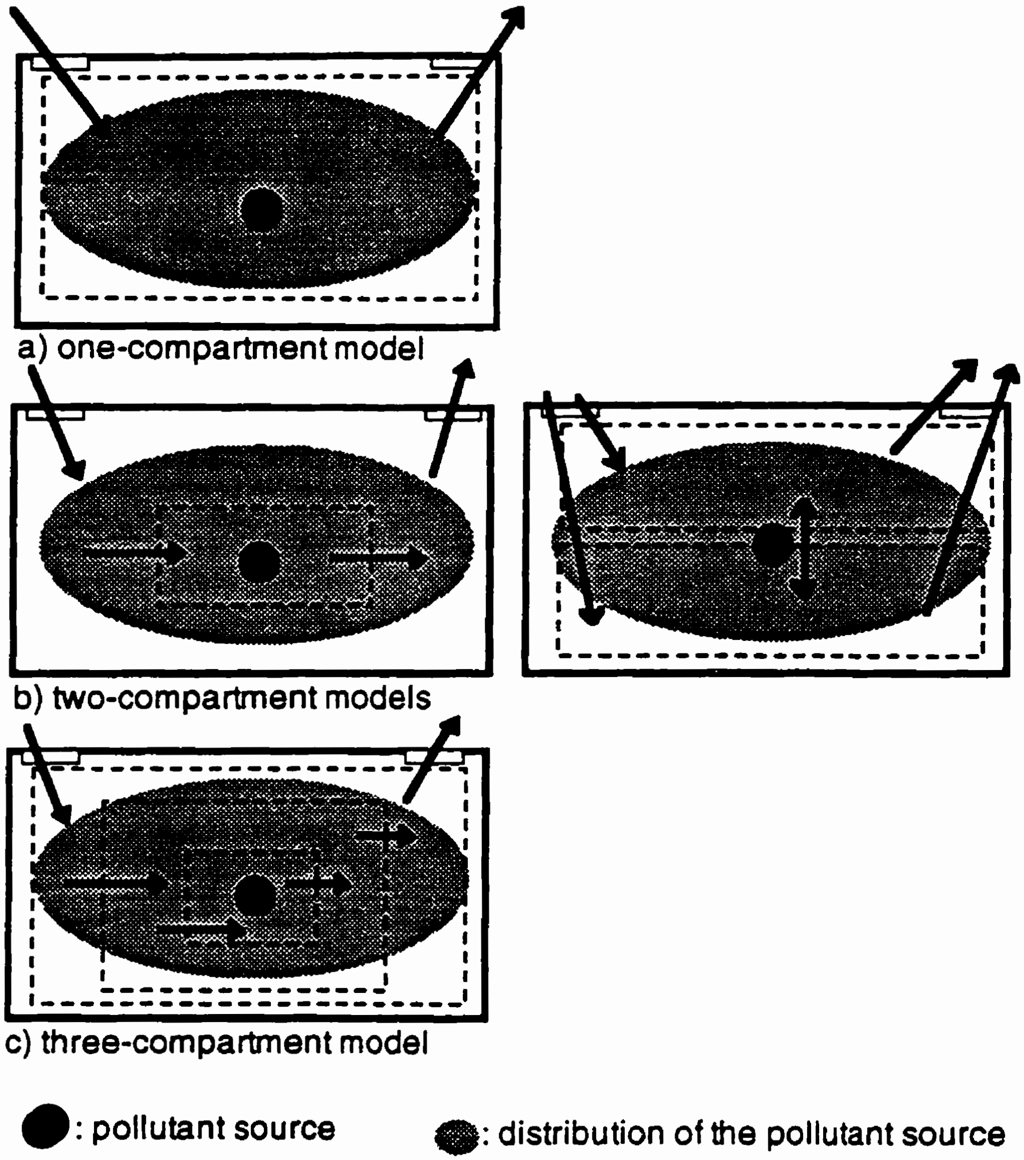


Figure 2.7: Examples of compartment models [49,110,116]

In Figure 2.6, formula 2.3 is obtained by re-arranging the terms in formula 2.0. For a fixed exhaust rate and a fixed source strength, the flow rate in formula 2.0 is replaced by an effective flow rate to obtain the definition of ε_{c3}. This flow rate q is the effective flow rate passing through the compartment in the middle of the room and is defined as follows [50,57,69,88,90,99,102]:

$$q' = \varepsilon c q$$

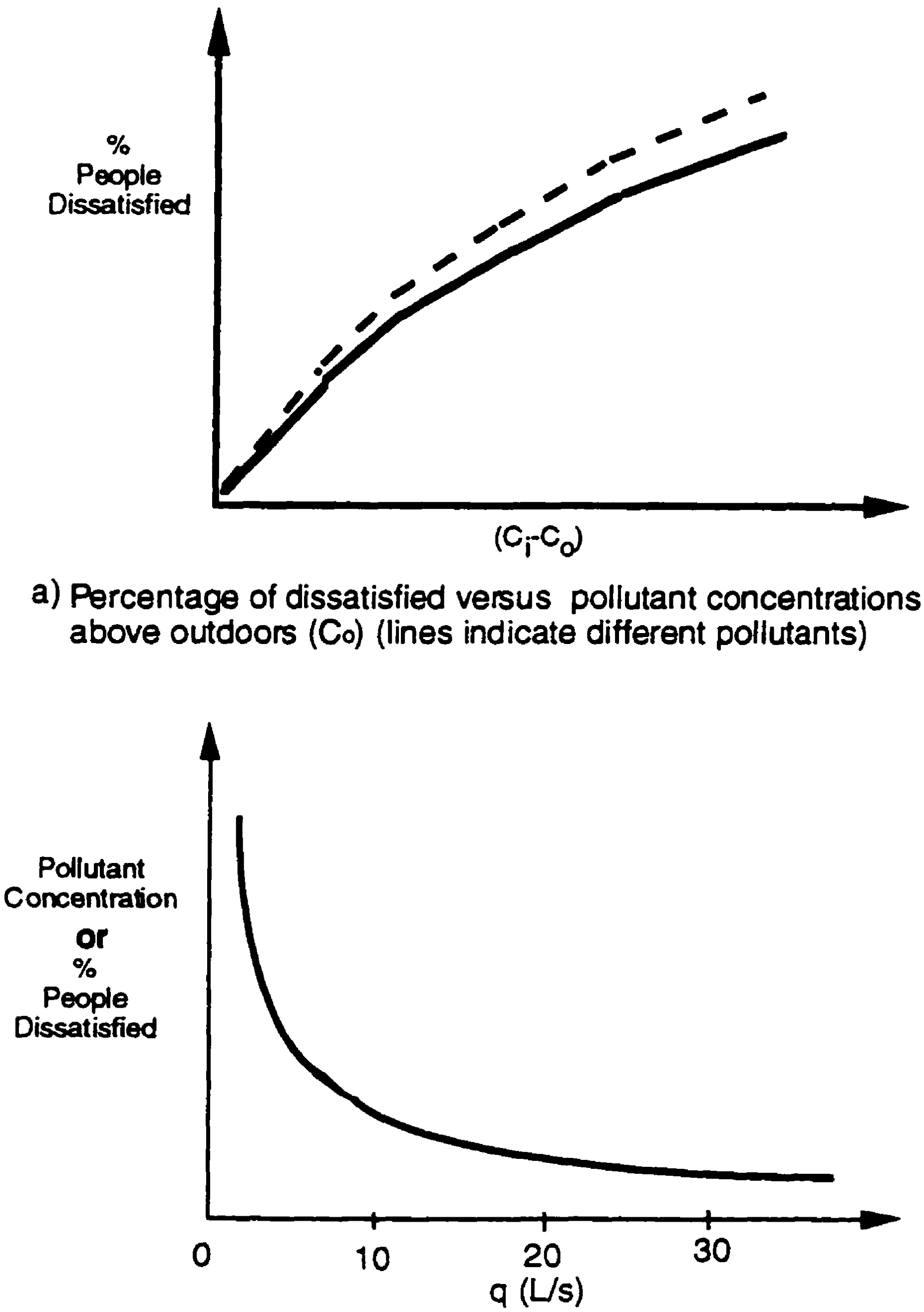
When this expressions is introduced in formula 2, the definition of ε_{c3} is obtained. The same assumption of an "effective" flow rate is used for formula 2.4 and 2.5.

In formula 2.3, the S and the q must be known in addition to the room concentrations of the pollutant to calculate ε_{c3}. If the pollutant source is a person, then S can be set to be equal to the production of CO_2 or VOC's multiplied by the number of people in the room generating the pollutant. If the pollutant source is a piece of furniture or a piece of equipment (e.g.: photocopier), the S can be estimated from the manufacturers' data of the products. In most cases, however, S rates (e.g.: $L/s/m^2$) are unknown and, the measurement of the S of a particular source must be obtained from experimentation over a sample of the source tested under controlled conditions. Another alternative is to simulate the source in the space using a tracer gas and measure the resulting concentrations. The outdoor air flow rate, q, can be measured using a tracer gas decay test as was described earlier as the value of n or $1/\tau_n$ used for the age-of-air method [88,119,125,132,133].

The value of ε_c in 2.4 is obtained by assuming that the maximum concentration for a pollutant in the room, should be less than what would be obtained under fully mixed conditions for the ventilation rate of 70 L/s per $100m^2$ prescribed by ASHRAE [49]. This is accomplished by setting the values of S, C_0 and q in formula 2 to constant values to obtain a pollutant control index or PCI [99]. First, the source strength, S, is modified to correspond to a given pollutant source strength, G_0, that is created by introducing small passive sources (e.g.: perfluorocarbons) over the floor of a building [105]. These sources are assumed to have a constant injection rate and the total injection rate is equal to the number of sources, n, multiplied by their emission rate (e.g.: L/s , m^3/hour) [99]. Next, the background concentration of the source, C_0, is set to be zero in formula 2 since the sources are initially absent from the room tested [105]. Finally, the value of q in formula 2 is set to a constant value equal to 70 L/s per 100 m^2 which is the prescribed rate by ASHRAE for office buildings occupied by 7 occupants per 100 m^2 [49,99]. This ideal or predicted outdoor flow rate is incorporated in formula 2.4 by using the constant, k, and the surface area, A, of the space [99]. Finally, formula 2.4 is obtained if these values of G, Co and q are introduced in 2 and, contrary to the other definitions, ε_c is defined as increasing with increasing C_i and the higher the PCI, the lower is the ε_c of the space [99].

The last definition of ε_c, ε_{c5}, is similar to the previous formulas except that perception units instead of concentration units are used. The effect of using perception instead of concentration units is to make the effectiveness dependant on human perceptions of odours. Fanger and other researchers have provided curves of human perception versus concentrations for pollutants such as CO_2 and volatile organic compounds [25,27,40,50]. Figure 2.8 shows the relationship between human dissatisfaction and contaminant concentration for CO_2 and different ventilation rates [27]. The relationship between the number of dissatisfied and the q is changing in the same manner as the relationship between room concentrations and q defined in formula 2.3. For a constant S, the concentration and the odour level of a pollutant decrease with increased q as shown [27,50].

Overall, the definitions of ε_c based on formula 2 are limited by the ability of the two-compartment model to actually predict the minimum concentrations in a room. Again, as was the case for age-of-air, the model predictions of the optimum efficiency may vary if a different model than perfect mixing is used for the flow in the room. It is also important to note that, for the case of a room under perfect mixing, the values of ε_c and ε_a should be equal [98,101,104]. Other limitations of these definitions are related to the measurement of the emission rates and the outdoor flow rates in the room [95]. Usually these values can not measured accurately because of the uncertainty over the pollutant's source or because the infiltration of outdoor air is unknown [95,98,101]. Also, the formula 2 assumes steady-state conditions in the room and does not account for sudden changes in the ventilation rates or in the temperatures in the room [95,98,101].



a) Percentage of dissatisfied versus pollutant concentrations (C_i) above outdoors (C_o) (lines indicate different pollutants)

b) Human dissatisfaction and pollutant concentration (C_i) versus ventilation rate (q)

Figure 2.8: Human perception versus pollution and ventilation (adapted from [25])

2.5.2.2. Definition of pollutant removal effectiveness based on concentration ratios

Concentration ratios such as those calculated by formula 2.1 and 2.2 provide the simplest way of expressing ε_c for a space [88,90,50,57,69]. The assumption behind these definitions is that ventilation effectiveness is high when pollutant concentrations are low in the space. The minimum concentration of the pollutant or the lowest concentration in the room for these ε_c definitions is assumed to be equal to the concentration in the exhaust. The exhaust concentration is assumed to represent the average pollutant concentrations for the room that would be obtained for perfect mixing conditions in the zone.

The definition of ε_{c2} is the same as ε_{c1} if outdoor air concentrations are zero and, if outdoor concentrations are equal to indoor concentrations, then the value of ε_{c2} is infinite. Usually, outdoor concentrations are expected to be lower than indoor ones and ε_C should always be positive [88,90]. Compared to formula 2.1, formula 2.2 includes a correction factor to include outdoor air concentrations.

These two definitions are simpler than the previous ones because they do not involve the measurement of parameters other than the concentration of the pollutant or the concentration of the tracer gas used to simulate the pollutant.

These definitions do not define an absolute value for ε_c because a ratio of concentrations does not include any information concerning the magnitude of the concentrations involved. This means that a very high value of ε_c does not guarantee that the concentrations are below the maximum recommended levels for the specific pollutant (e.g.: 1000 ppm recommended by ASHRAE for CO_2 [49].

2.6. Tracer gas techniques used for VE

As introduced earlier, tracer gas methods for VE measurements are used to obtain the comparison between predicted and actual room air distribution (ε_a) or the comparison predicted and actual room concentrations of pollutants (ε_c) (see Figure 2.1, p.15). While the previous section described some of the limitations of the numerical models used to define VE, this section describes the limitations of the tracer gas methods used to measure VE in the field and in experimental chambers.

The steps involved in the application of tracer gas methods can be identified by 1) the choice of a tracer gas, 2) the selection of an injection scheme for introducing the gas into a space, 3) the collection of the gas and 4) analysis of the concentration data. These steps are shown in Table 2.1 where the techniques used for measuring ε_a and ε_c. are compared [53,78,80,84,88,90,112 to 126].

Table 2.1: Steps involved in the tracer gas methods for ε_a and ε_c [108,119]

	ε_a	ε_c
1) Tracer gas selection	-non-toxic -same density as air -easily detectable -absent from the room air background -not captured by room furniture or room finish	
	examples: carbon dioxide (CO_2) sulphur hexafluoride, SF_6 nitrous oxide refrigerants	examples: carbon dioxide (CO_2) tobacco smoke volatile organic compounds perfluorocarbons
2) Injection type	-outdoor air supply or room air	-room air -continuous
Injection duration	-continuous -pulse -equilibrium	-continuous
3) Collection of data	-tracer gas analysis on site -grab sampling (bags, captors, tubes) and off-site analysis	
4) Analysis of results	age-of-air	-concentration ratio -two-compartment model

Compared to chamber studies where there are few limitations to apply these techniques, field testing studies are subject to more constraints and limitations. This is because, at each of the steps followed through their application, the techniques must not affect the health of the people present in the office spaces. They must be performed in a manner that respects the assumptions of the models on which they are based.

2.6.1. Tracer gas

The first step involved in all the tracer gas methods consists in selecting the correct tracer gas according to the criteria listed in Table 2.1 [108,119]. The criteria are not listed in order of importance but the governing criteria in the selection are usually the toxicity and the detectability of the gas [108,119]. Density, presence of the gas in the background and absorption are usually less of a concern for most gases [108,119]. So far, however few gases were found that can fulfil all these requirements and, for this reason, different tracer gases have been proposed and used by researchers.

Among the list of tracer gases shown in Table 2.1, only CO_2 can satisfy most of the requirements for field testing in the presence of occupants or the toxicity criteria [108,119, 123]. The advantage of CO_2 is that it has a density similar to the air (1.53 times the density), it is also easy to detect (using portable and inexpensive infra-red detectors) and it is not absorbed by room furniture or room finishing [119]. The main disadvantage of CO_2, however, is that it is generated by occupants and therefore, variations in the background concentrations of this gas must be introduced in the methods [132,133].

In relative terms, all the other gases listed in the table can pose a more important health risk for the occupants than CO_2. Potential risks include the possibility of accidental or undetected leaks of the gases into an occupied room or their decomposition into more toxic compounds as they enter the hot components of a heating system (e.g.: baseboards, gas or oil burners) [122]. For ε_c, the tracer gases used are usually a pollutant (e.g.: VOC's) and therefore this limits the application of the methods to unoccupied rooms, or it requires the use of subjects that are accepting to be willingly exposed to these gases. This acceptance is difficult to obtain in buildings where a large number of people may fear the gases or where people are already concerned for their health (e.g.: chemical susceptibility, pregnancy, stressed work relations) [95,99].

2.6.2. Injection techniques

The second step in the tracer gas methods is to determine which injection technique is to be used for measuring VE [108,112,113, 114,118 to 121,124,125]. This includes selecting the location as well as the duration and flow rate used for the injection. Although there are variations, usually, for ε_a, the gas is injected into the outdoor air supply or directly into the room and, for ε_c, the gas is injected to simulate the pollutant of concern (e.g.: point source of tobacco smoke, diffused floor source such as carpets) in the room [88,90].

For either ε_a or ε_c, the injection can be made continuously (up to a few hours), by using a pulsed injection (few minutes) or by injecting the gas until room concentrations have become uniform using mixing fans located throughout the space [119,120]. Most techniques for ε_c make use of continuous injection schemes because pollutants are usually generated in this fashion in a room. In either cases, the duration and the rate of injection of the gas (volumetric or mass flow rate) determine the resulting concentrations of the gas in the room [119]. Based on the dimensions of the room and based on the estimated ventilation rate, the injection rates and duration of the injections are adjusted to obtain concentration levels well above the detection limits of the gas analysers used [119, 120].

These injection techniques are usually not suited to be applied under the conditions normally observed in office buildings because of the migration of the gas to unknown areas and because infiltration or the effect of VAV systems is not measured [88,95,99,100]. This is mostly due to the complexity and variety of the ventilation systems found in office buildings [100]. For example, in most buildings, usually more than one ventilation system is used per floor (e.g.: one system in the centre and one system for the perimeter of the building) and systems can be responsible to deliver and remove air from more than just one floor (e.g.: one central systems delivers air to all the floors and another system distributes air to the perimeter zones) [88]. This means that the tracer gas can migrate from floor to floor and in between ventilation systems and, consequently, after a while, it becomes impossible to determine what zone or what system is labelled by the gas. Also, after the gas is injected, a certain amount returns into the supply air and thus the gas ends up labelling both outdoor and recirculated air [121]. Finally, in all these techniques, the effect of natural infiltration and exfiltration (natural outdoor air flow caused by pressure difference between the inside and outside) and the variations of airflow introduced in time by VAV systems in the building are usually neglected even though these air quantities may significantly affect the evaluation of ε_a or ε_c [88,103,105,106,111,115,118,121].

Because most of the above factors are not included in any of the numerical models described in the previous sections, the measurement results of VE in the field can sometimes become meaningless [88,90,99,100,103]. In order to circumvent these limitations, most injection techniques would require that ventilation systems be operated at constant outdoor airflow, that the interior building zones be isolated from each other and, that infiltration be measured or eliminated [99,100,103]. This is rarely a practical solution because actual ventilation systems and buildings are not airtight throughout and large interior zones can not be sealed effectively to prevent tracer gas migration. Also, in the end, whatever modification is made to make the building comply to a particular injection scheme's requirements, the changes introduced will disturb the normal operation of the building. The result is that the conditions studied are not the actual conditions but some modified and controlled version of the real conditions supposed to be studied.

The measurement of ε_c is however less dependant on these limitations than for ε_a, since the tests aim at simulating a pollutant source as it actually appears and does not necessarily involve any assumptions concerning the dynamics of the air flow [100]. For ε_a however, it is critical that airflows conform to the assumptions of a simple room similar to the one-compartment model described earlier because deviations from this ideal condition affect both sampling and analysis of the tracer gas concentrations used for VE calculations [99,100,103].

2.6.3. Sampling locations

The sampling of the tracer gas in the field is mostly limited because it is difficult to select the most appropriate locations for the measurement of the gas [88,99,100,103]. In most cases, a normal office building is constituted of several hundred worksites and for each site, there is a corresponding number or air supply diffusers and air returns or evacuations. In some cases, the situation is even more complex if the airflows are varied during the day as the outside temperatures change [100].

As a simplification most techniques involve the selection of air returns, air supplies and room locations that are judged to be critical or typical of the space [78,88,100]. Nevertheless, during this selection process, there is usually a loss of information concerning the particular conditions in different locations of a room and a "typical" location may not be easy to define if ventilation conditions vary from room to room and even from worksite to worksite [78,88,100]. In some of these cases, passive air returns (non-ducted returns) have been observed to work partly as air evacuation or as air supplies as the pressure between the room and the evacuation change [99,103]. If this is the case, what was assumed to be a sample of the gas in the return air is in fact partly a sample of recirculated air and partly a sample of evacuated room air.

2.6.4. Tracer gas concentrations measurements

Contrary to all the other steps involved in the tracer gas techniques, there are usually little error introduced in the actual measurement of the tracer gas concentrations [118,119,126,142]. The analytical instruments used to measure the gases are usually capable of measuring concentrations with less than 5% error over the maximum concentration value measured [142]. This error is only analytical and the actual error of the method should include all the other factors presented so far. For on-site analysis of the concentrations, however, some limitations occur when the techniques involve the use of bulky apparatus (e.g.: gas chromatograph) and the deployment of tubing throughout the office spaces [88,102]. This limitation is not important if portable instruments are used or if grab samples are used and later analysed off-site [88,102].

2.6.5. Overall limitations of the techniques

In general, from the above, it can be concluded that the further the actual field conditions are from the models' predictions and the less the measurment methods are accurate or even applicable in the field. Comparatively however, there seems to be less difficulty in using methods for ε_c than for ε_a since ε_c measurements simply test pollutant concentrations as they occur and, in most cases, they do not involve assumptions concerning the airflows into the room [100]. The above limitations of the techniques are only a partial overview of the constraints affecting the performance of tracer gas measurement techniques in the field. Further discussion on these aspects can be found in specialised reviews on the subject [118,119,126,142] or within the discussion of the results provided by individual authors as discussed in the next section.

2.7. Ventilation efficiency results

Since VE definitions have changed over the past decades, the comparison of VE measurement results from different studies must take into account the definitions and the methods used at a particular time. For example, although most definitions and methods for VE originated in the 1980s, experiments by Lidwell in the 1960s provided some of the first results of ε_a and ε_c using tracer gas techniques [52]. In these tests, nitrous oxide was used to measure ε_a using an "equivalent ventilation" rate similar to τ_n and, the measurement of acetone concentrations generated by a cotton wick exposed to the atmosphere of a room were used to obtain ε_c [52].

Following these early attempts and for the next twenty years, the measurement of VE using tracer gas was mostly limited to evaluate the "air change rate" of a space [88,106,111,115,118,121,125,133] instead of being the comparison between "actual" and "predicted" air change rate conditions. During this period, a considerable amount of data became available on the infiltration rate values of buildings that are an important factor for energy consumption [88]. Some studies were also aimed at measuring outdoor flow rates using tracer gases but, air velocity measurements in ducts instead of tracer gas methods seem to have been preferred for this application [88]. Because each office has its own infiltration and outdoor flow rates, results of air change measurements can not be compared directly unless a concept such as VE is used [78,100].

The period between the mid-1980s until today produced the first series of results with a specific mention of ε_a and ε_c as distinct parameters for VE (see Table 2.2). In a first stage during the period from 1980 until the end of the 1990s, most measurement results of VE were obtained in controlled test chambers to verify the theoretical predictions of the models proposed and, only a few isolated studies were performed in actual buildings [53 to 86]. Since the beginning of the 1990s further work was accomplished by other researchers [87 to 104] to replicate the results from this first period of research and, the use of computer analysis was introduced to predict VE in "virtual" environments based on different flow models [127 to 130].

It would have been expected that the accumulation of results on VE measurements over these past fifteen years would have resulted in providing a series of guidelines for the proper methods of measurement of this parameter [100]. By obtaining more results from actual building measurement studies, it would have been also expected that typical or representative values of VE would have been established to characterise existing building ventilation systems. Finally, it would have been expected that a consensus would have been reached on the proper basis for comparing different results from different methods.

Unfortunately, until now, this is not the case since the measurement methods for VE that are the foundation of VE results are still seriously put into question [100]. For example, in a recent review of their experiments on the use of tracer gas methods for ε_a and ε_c, in buildings, Fisk and colleagues observed that the age-of-air method was "impractical or inappropriate" for many large complex buildings and they also suggested that ε_c methods required further study [95, 103]. In another study by Shaw and colleagues, the same methods were judged to be inappropriate to compare different types of systems [98,101]. They also observed that, contrary to expected, ε_a was found to decrease with increasing ventilation rate and that ε_c results followed predictions better than ε_a [98,101]. Other studies have not been as categorically negative in their evaluation of the age-of-air techniques but they did not deal with the practical aspects of applying the methods [104].

2.7.1. Results from ε_a measurements

Measurement results obtained from test chamber and field studies for ε_{a1} and ε_{a2} are shown in Table 2.2 for the period between 1985 and 1995 [74,76,83,86,95,97,98,101]. The list includes the experiments performed in test chambers of size comparable to the size of a small office space and field measurements performed in different types of office buildings.

Other types of results for ε_a have been obtained using the numerical simulation of the age-of-air in simplified rooms [127 to 130] and are not included in the list because, contrary to the experiments listed in the table, numerical "experimentations" provide results that are free of the constraints related to actual field measurement. In these simulations, all the variables of the problem (e.g: air flows, temperatures, dimensions of the room, number of diffusers) are set to constant values in models developed for fluid-flow dynamics. Since the models and their variables are fixed and known (deterministic model), the results represent what the "ideal" conditions would be in a room with little or no variations in the flow patterns or pollutant distribution. Accordingly, contrary to test chamber or field measurements, the assumptions made for the ε_a definition (e.g.: piston-flow, steady-state conditions) will always be validated in numerical simulations. Therefore, these simulations provide a prediction of the range of ε_a results expected in a room and indicate design objectives while the direct measurement of ε_a allows to validate the definition of this parameter for the field.

Table 2.2: Summary of air exchange efficiency (ε_{a2}) measurements results

Authors, date	Type of study	Definition‡	Range observed (ε_{a2})*
1) Sandberg, 1985 [97]	chamber (n=35)	ε_{a1}	cooling: 120% to 240% heating: 20 to 40%
2) Seppanen, 1986 [76]	offices (n=23)	ε_{a2}⁺	>82% and typically equal to 100%
3) Persily, 1986 [74]	offices (n=3)	ε_{a2}	100 to 120%
4) Persily and Dols, 1989 [86]	offices (n=9)	ε_{a2}	90% to 110%
5) Offerman, 1988 [83]	offices (n=5)	ε_{a2}	65 to 70%
6) Fisk and Faulkner, 1988 to 1991 [in 95]	offices (n=11)	ε_{a2}	VAV and constant ventilation systems:100% to 140%
7) Fisk and Faulkner, 1995 [103]	chamber (n=26)	ε_{a2}	vav systems,heating, cooling: 70% to 110%
8) Shaw, 1992 & 1993 [98,101]	chamber (n=16)	ε_{a1}	isothermal: 112 to 240%
all of the above		ε_{a2}	10 to 140%

‡: original definition used by authors

*: values have been rounded to the nearest 5% range.

⁺: the value of ε_{a2} is equal to twice the value of ε_{a1} ($\varepsilon_{a2}=2\varepsilon_{a1}$)

The application of tracer gas techniques in test chambers and in office buildings shown in Table 2.2 indicates that the values observed for ε_{a2} (perfect-mixing) varied between 10% and 140% or over a 120% range. Publications by Fisk and Faulkner in 1992 summarised a part of these results (experiments from studies 2 to 6) and proposed to calculate a confidence interval for the field measurement results [95]. Based on a 95% confidence interval, they estimated that ε_{a2} in office buildings would be at an average of 100% and would vary by 20% or over a 40% range. Also, they concluded that differences of more than 20% in results may be due to errors in the measurement techniques and would not necessarily be an indication of a difference in ε_a [95].

The error in ε_a values is comparable to the error observed for the estimation of outdoor air infiltration rates using tracer gases that are methods estimated to have a 10 to 20% error [142]. Because the age-of-air measurements are based on mixing assumptions, it would be expected, however, that the error would be greater than for air change measurements. Therefore, the 20% error value proposed by Fisk and colleagues [95] could be a conservative estimate when this value is compared to the air change rate error for a similar and relatively better documented tracer gas technique.

Sandberg's results in test chambers showed that air supply temperature could be influencing ε_a by a factor of more than three [97]. For the worst case conditions, efficiency could be as low as 20% with a warm air supply and the efficiency could be as high as 240% for a cold air supply temperature. In comparison, the other results shown in Table 2.2 for the measurements of ε_{a2} are closer to the higher efficiency range reported by Sanberg [97] with values above 60% for ε_{a2}. These results for the worst cases presented by Sandberg were only representative of a test chamber condition with ventilation used for heating and is usually not a recommended practice to follow in a normal office building.

The last set of experiments by Shaw [98,101] were performed with supply temperatures close to the air temperatures (isothermal conditions) and showed a range similar to the cooling experiments reported by Sandberg [97] and the other authors. This study also reported that the effect of changing furniture layouts in the room may influence efficiency results by up to 10% [98,101]. The effect of room layouts were not studied or discussed in details in the other studies since most values of efficiency were close to each other or this factor was not studied.

As mentioned earlier, the above results are difficult to judge in absolute terms since the authors of the most recent studies (7 and 8 in Table 2.2) do not seem to consider the age-of-air method to be a reliable method for field measurements or even for chamber measurements [86, 87]. These limitations had already been identified by other research efforts performed at McGill by Farant and Auger based on the measurement of VE in office buildings [91] and test-chamber research [89].

Based on these conclusions and the results shown in Table 2.2, there appears to be a contradiction between the low confidence in the methods and the confidence in the results obtained by different researchers. Assuming that the range of values observed is accurate then, ε_a could be a problem in certain cases [97] where a room is heated improperly through the ventilation instead of an independent heating system (e.g.: baseboards) is used. If the methods are correct, then, also, the average value observed in offices of ε_{a2} of 100% would indicate conditions close to the assumptions of perfect mixing with small variations of 20% in certain cases.

If the methods used to obtain the results shown in Table 2.2 are not correct however, then, efficiency results can not be compared directly and each experiment is almost unique [100]. However, because there is some level of confidence in these tests, it would seem that in practice, the measurement results of ε_a should be within the ranges shown. Because the experiments results available so far for the measurement of ε_a are limited however, it would be difficult at this point to determine whether ε_a is a problem or not in office buildings [100].

2.7.2. Results from ε_c measurements

Measurement results obtained from test chamber studies for ε_{c1} and ε_{c2} are shown in Table 2.3 for the period between 1982 to 1995 [55,57,98,101,103]. The list includes the experiments performed in test chambers of size comparable to the size of a small office space and, contrary to ε_a measurements presented in the previous section, the list does not include field measurement results. Also, results for the other definitions of ε_c presented in section 2.5 are not available and therefore, these definitions do not appear in the table. Similarly to ε_a, results for ε_c have been obtained using the numerical simulation of different ventilation alternatives but these results are not presented since they do not pertain to the "field" measurement of ε_c.

The first study in the table represents one of the earliest attempts made to measure ε_c in a test chamber using the definition of ε_{c2} based on a two-compartment model [55]. Results are shown for only three experiments for which ε_c was obtained by the simulation room conditions considered to be representative of a normal or typical office room found in Sweden. The authors discussed the impact of using a light bulb (100W) on pollutant distribution simulated in the centre of the room (using N_2O) and the effect of the location of the source on the measurement results [55]. These results are however limited to a small number of experiments.

Table 2.3: Summary of ε_c measurement results

Authors, date	Type of study	Definition	Range observed
1) Malmstrom and Ahlgren, 1982 [55]	chamber (n=2)	ε_{c2}	isothermal: 0.75 and 0.85
2) Skaret and Mathisen, 1983 [57]	chamber (n=18)	ε_{c2}	0.2 to 1.4
3) Shaw, 1992 & 1993 [98,101]	chamber (n=16)	ε_{c2}	isothermal: 0.51 to 1.22
4) Fisk and Faulkner, 1995 [103]	chamber (n=5)	ε_{c1}	vav systems, heating, cooling: 0.63 to 1.3
all of the above		ε_{c1}, ε_{c2}	0.2 to 1.3

Tests performed by Skaret and Mathisen in the same period provided a more extensive set of results for a test chamber also simulating a one-room office space [57]. These results were summarised and integrated in the CEC guidelines as shown in Figure 2.9 [50]. According to these results, the values of ε_{c2} can be observed to vary between 0.2 and 1.4 depending on the strategy used to ventilate a room [50]. The worst case of 0.1 corresponds to the lowest room/supply temperature difference and for what is described as "displacement" ventilation. The best case also corresponds to displacement ventilation but for air supply temperatures above room temperatures.

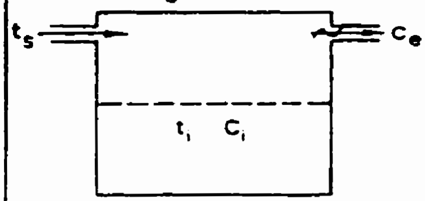
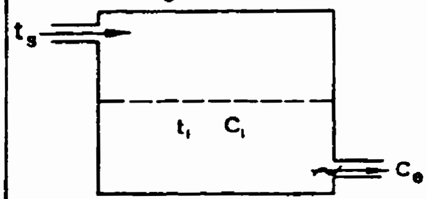
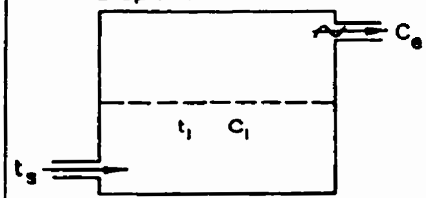
Ventilation Principle	Temperature difference between supply air and air in breathing zone, $t_s - t_i$ °C	Ventilation Effectiveness
Mixing ventilation 	< 0 0 - 2 2 - 5 > 5	0.9 - 1.0 0.9 0.8 0.4 - 0.7
Mixing ventilation 	< -5 0 - -5 > 0	0.9 0.9 - 1.0 1.0
Displacement ventilation 	> 2 0 - 2 < 0	0.2 - 0.7 0.7 - 0.9 1.2 - 1.4

Figure 2.9: Summary of ε_c results for different ventilation arrangements [50]

Most North American buildings operate using mixing ventilation as shown in the top of Figure 2.9 while mixing ventilation, as shown in the middle, is usually restricted to special ventilation applications (e.g.: clean rooms, computer rooms). For the cases of air supplied and delivered in the top of the room, ε_c can be as low as 0.4 if supply temperatures are above room temperatures [50]. These values are representative of a small room and it is expected that these values will vary as the size of the rooms studied deviate from these conditions.

Further work by Fisk in test chambers provided a range of ε_{c1} for a simulated office room with air flow rates typical of VAV systems and different cooling and heating conditions [103]. They used a distributed source of pollutant simulated using perfluorocarbons as a tracer gas. The range observed of ε_c in this study (0.6 and 1.3) is similar to the ranges observed by the other two previous studies. The authors also indicated that the presence of human source of heat (simulated by a mannequin) had an influence on the distribution of the pollutants and therefore influenced ε_c results [103]. Also, they observed that the values of ε_a were not representative of the values of ε_c because results with highest values of ε_a did not necessarily correspond to high values of ε_c. This means that exposure to pollutant concentrations can not be evaluated from the age-of-air results because the locations of heat sources in the room disturb the air flow patterns in sub-zones of the room and therefore the "perfect-mixing" assumption for age-of-air is not verified.

The series of measurements performed by Shaw and colleagues produced results within a range of values of ε_c similar to those obtained by the other studies shown in Table 2.3 [98,101]. The study showed that ε_c was higher as the volume flow of outdoor air q in the room increased which contradicts equation 1 and 2 presented earlier. The contradiction is assumed to be due to the influence of turbulence in small portions of the space caused by higher flow rates. They concluded that ε_c at the higher flow rates was reduced because of these increased turbulence [98,101]. Since this trend was not observed in other studies, these results may be different because of the difference in the experimental conditions studied because, for the other studies, furniture was absent or was limited (e.g.: desk, chairs) in the room. The effect of furniture observed by Shaw and colleagues may therefore be more accurate in representing actual field conditions observed in buildings.

As mentioned earlier, the relationship between ε_a and ε_c is not yet established based on current research results but, comparison of table 2.2 and 2.3 can be used to discuss some of the aspects of the relationship between these two parameters. Even though different definitions and methods were used to obtain the values in the tables, the results for ε_a and ε_c appear to vary over a similar range (ε_a: 10% to 140% versus 0.2 to 1.3 for ε_c) for results for tests conducted in test chambers only.

The difference between chamber and test conditions results may be due to a tendency for researchers to simulate relatively worse conditions than the conditions existing in office buildings. Nevertheless, this difference could also be explained by the fact that the methods applied in the field do not produce the same results when they are applied in test chambers as concluded by Fisk. Most likely, there is not a single relationship between ε_a and ε_c although this is based only on the available definitions of these terms. Different definitions may well show that there is a good relationship between ε_a and ε_c if other approaches are adopted [100].

2.8. Field measurement of VE

Until today, the development of building science in fields parallel to VE research has provided some important theoretical and experimental findings that have helped to understand and predict the behaviour of air movements in buildings or in rooms in general [134 to 147]. For an office space typical of the representation shown in Figure 2.10, VE is affected mostly by room conditions and ventilation.

All the VE results described earlier have indicated that room conditions may affect VE by a certain factor. As shown in Figure 2.10 c), factors included with room conditions can comprise the air supply (Ts) and room temperatures (Ta), diffuser flow (q), air velocities (Va) and to a lesser extent relative humidity (rh). Figure 2.10 shows a typical air distribution pattern recommended for a ceiling mounted diffuser that discharges air horizontally and that is used in most North-American buildings [134]. The air enters a diffuser that is designed to project the air along a certain distance in the room to create the correct conditions for thermal comfort and distribution in the space. This air is then exhausted by a series of return grilles located on the ceiling or the plenum of the room.

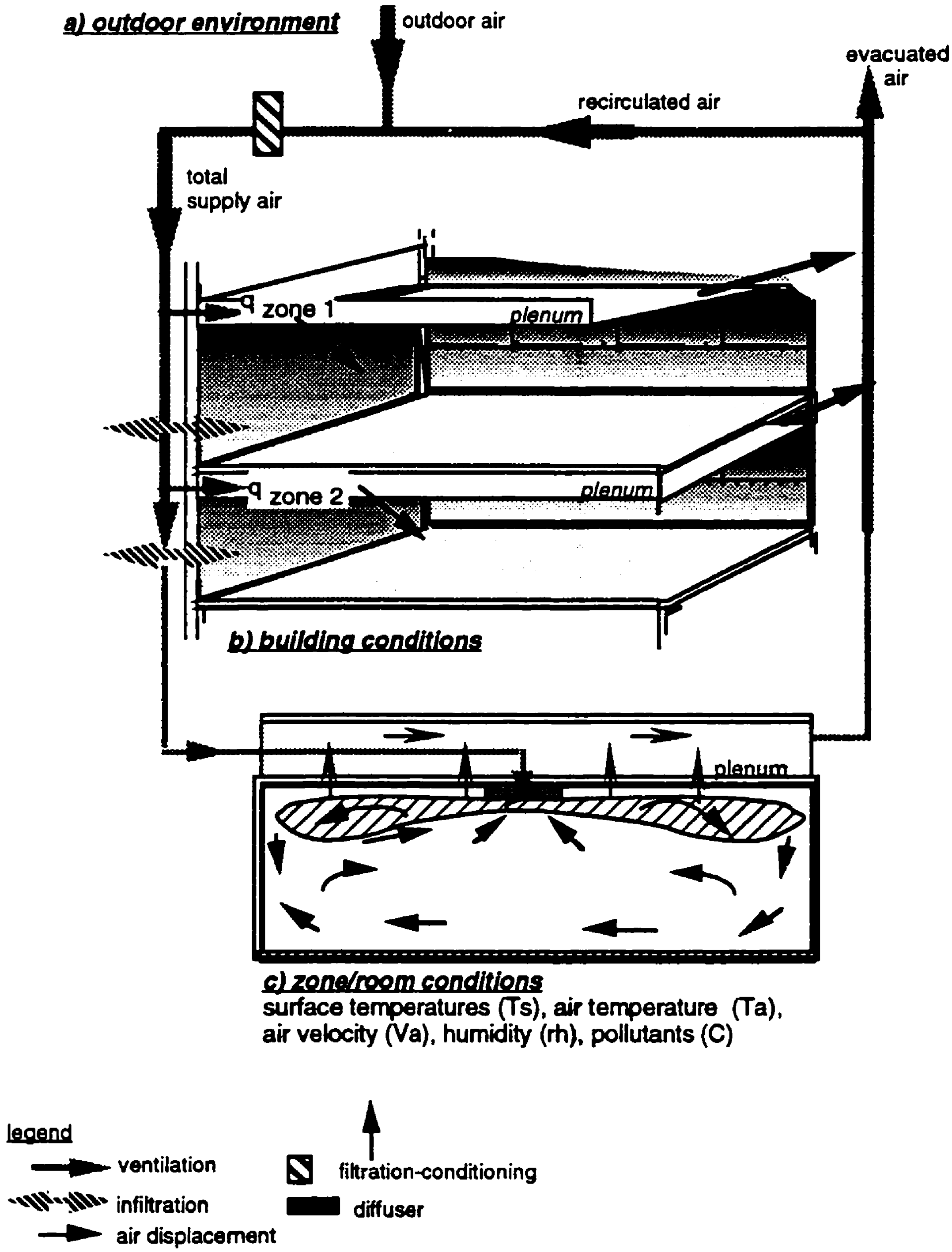


Figure 2.10: Parameters encountered in the field measurement of VE

For a given type of diffuser (e.g.: circular, square) the projection or "throw" of the air is affected mostly by temperatures and diffuser flow rate [134]. The temperature differential between the air in the room (Ta) and the temperature of the supply air (Ts) is referred to as ΔTs (Ts-Ta). A negative ΔTs is assumed to be better because it insures that the air from the diffuser is cooler than the air in the room and it will tend to drop in the occupied zone because of buoyancy or the movement of air masses of different temperatures and cause a stratification of temperatures. Changes in q will change the projection of the air into the room and this effect can be relatively important for ventilation efficiency for VAV systems [134].

Stratification of the air in the room is influenced by the differences between air temperatures (Ta), floor temperatures (Tfloor) and wall temperatures (Twall) [148]. Resulting air velocities in the room (Va) are affected by both temperatures and the flow rate of the air going into the room. It is expected that air velocities will augment with q and with increased temperature differentials (ΔTs) in the room because of increased buoyancy. Air velocities, Va, can be assumed to correspond to better ventilation efficiencies and can be evaluated using an index such as the ADPI (air diffusion performance index) that is a weighted average of Ta and Va for the room [139,140]. Relative humidity (rh) can be assumed to have only a small effect on effectiveness and air exchange efficiency compared to temperature and diffuser flow rate.

In the field, the parameters defined in the previous section must be contained within certain limits to provide thermal comfort in addition to proper VE. These limits indicate the correct combinations of temperature and relative humidity and air velocities for the comfort of the occupants. Conditions found in actual buildings are expected to vary around these limits Figure 2.11 [148,149] shows the temperature limits that are considered acceptable for thermal comfort based on a maximum of 10 to 20% of the occupants being dissatisfied. Although borders for the temperature scales have been modified for humidity in a later version of the standard, temperatures for comfort are between 23 and 29 °C for summer and between 20 and 23.5°C for winter. These limits are for 50% relative humidity and for mean air velocity equal to, or less than 0.15 m/s (nondirectional). Air velocities influence comfort differently depending on air temperature but, ASHRAE recommends a maximum of 0.15 m/s for winter and a maximum of 0.25 m/s for summer. For summer conditions, air velocities can be increased up to 0.8 m/s if air temperatures are up to 28°C.

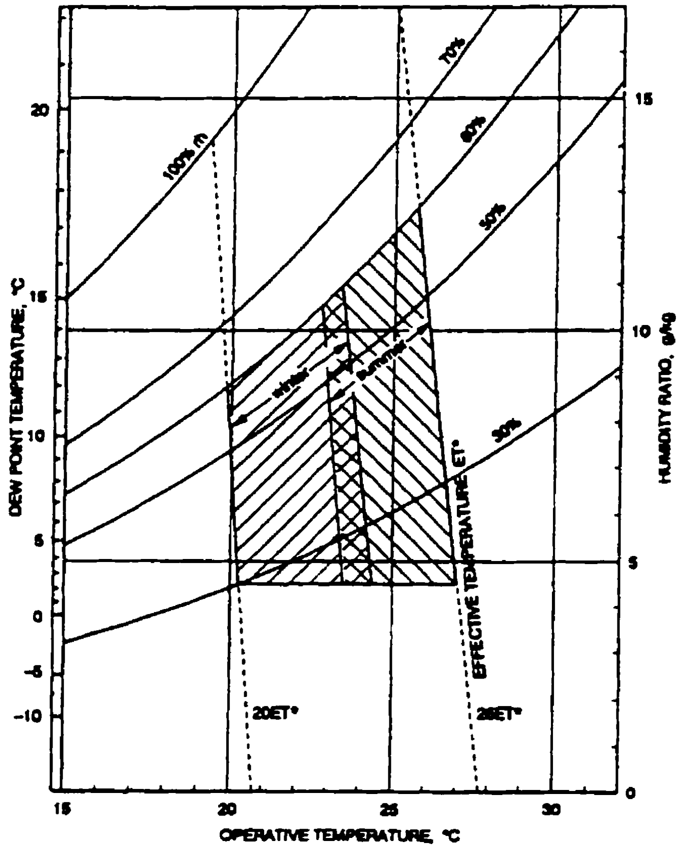


Figure 2.11 : ASHRAE Comfort Chart [149]

Most of the parameters mentioned so far will have an effect on both ε_a and ε_c while for ε_C, pollutant concentrations in the air supplied by the ventilation systems will also affect the results obtained with the different definitions (2.2,2.3,2.5) based on ratios of contaminants in the occupied space versus concentrations in the return of the ventilation systems. Carbon dioxide measurements in high-rise office buildings were performed by Shaw and Reardon [132] to determine how well mixed the indoor air was and how the occupied zone concentrations compared with air return concentrations. Figure

2.12 shows typical results from measurements in the return air of the ventilation systems and in the occupied zone of a typical office building floor. The authors concluded that CO_2 generated by occupants was mixed quickly and thoroughly with the indoor air and that, therefore, CO_2 measured at the return air was an adequate measure of the average floor concentrations [132].

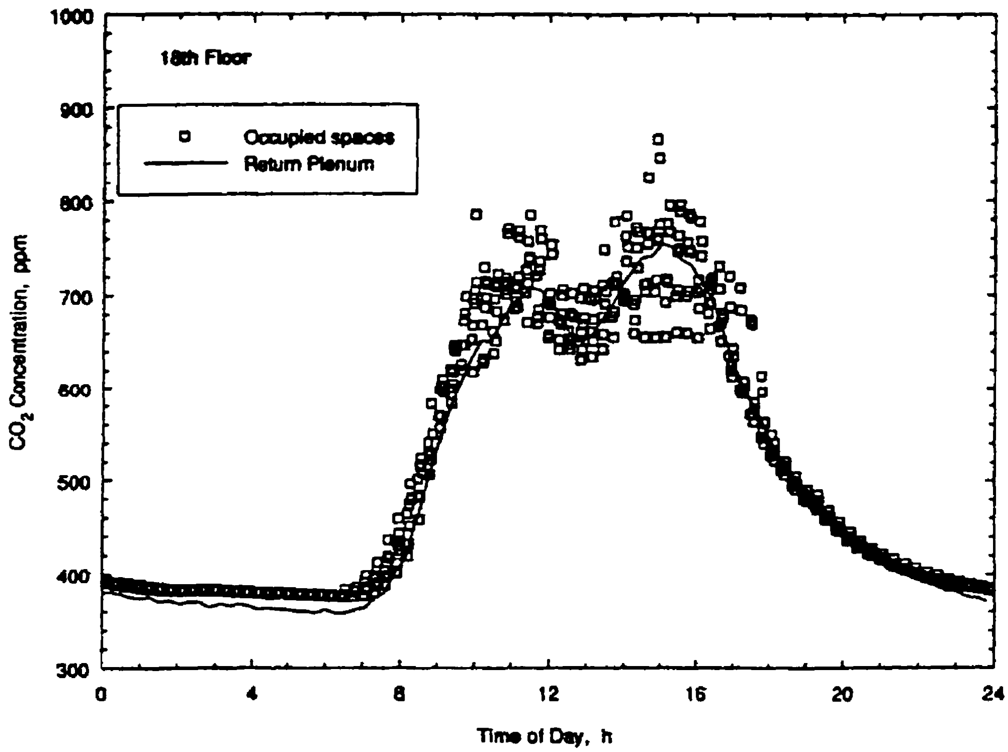


Figure 2.12 : Typical CO_2 in an office building (with permission from [132])

The ASHRAE standard 62-89 provides a chart of CO_2 production as a function of physical activity performed by workers [49]. Figure 2.13 reproduces a chart found in the standard that details the relationship between CO_2 production and activity levels. Activity levels are classified as being very light, light and moderate and production rates of CO_2 are shown to increase as a function of activity level. For an activity level of 1.2 met (1.0 met=18.4 Btu/h·ft^2)

corresponding to light sedentary activity, the generation rate of CO_2 is taken to be 0.30 L/min. For this level, a ventilation rate of 7.0 L/s is required to maintain concentrations below 1000 ppm assuming an outdoor concentration of CO_2 of 300 ppm [49]. Greater outdoor air ventilation rates are required as activity levels increase and ventilation must be adjusted accordingly.

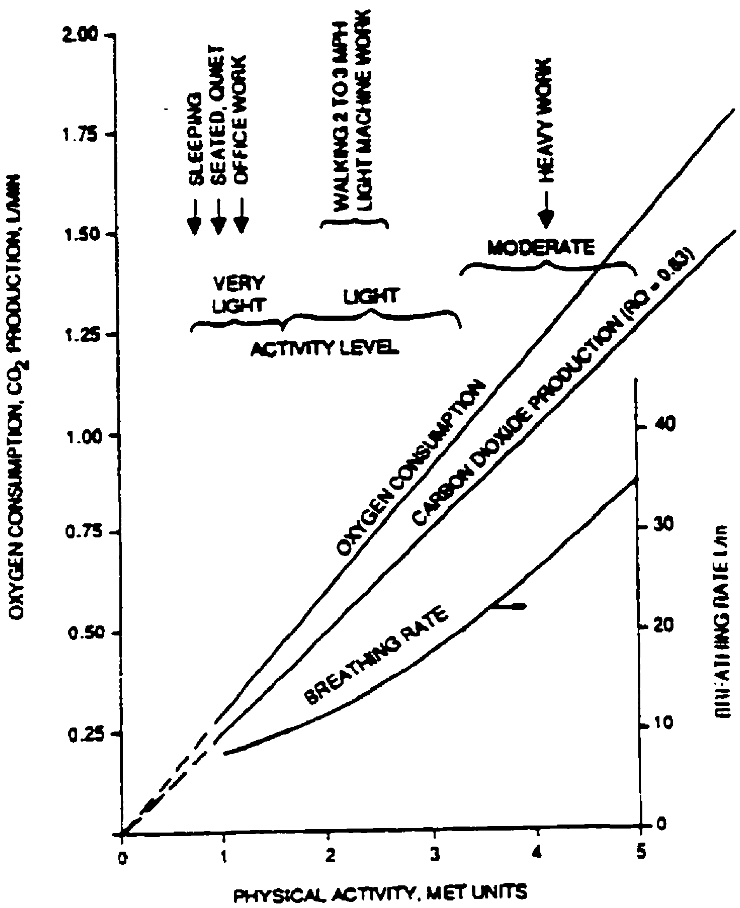


Figure 2.8 : Oxygen consumption and CO_2 production as a function of physical activity [49]

The main source of variation on VE due to outdoor conditions can be attributed mainly to solar radiation and infiltration of air (n') through the building envelope. Solar radiation will have an effect similar to that caused by raising indoor temperatures, while infiltration will vary the amount of outdoor air actually reaching the interior. Assuming that a building acts as a relatively rigid barrier against these factors and that the ventilation system is designed properly, the effect of solar radiation and infiltration should be much smaller than the effect of ventilation and room factors discussed earlier. Nevertheless, existing studies suggest that infiltration could, in some cases be an important factor in influencing VE and identified a need for the evaluation of this parameter in greater detail.

2.9. Discussion

In practice, a standard VE definition and measurement method for VE would be useful to compare and evaluate the performance of ventilation systems in different types of office buildings. With a standard value of VE for an indoor space, it would be possible to establish common objectives and guidelines for the design and the optimisation of a space with respect to IAQ and energy conservation. Before a method can be adopted as part of a ventilation standard, however, the main theoretical and practical limitations found in the methods proposed over the past fifteen years must be overcome.

As noted in this chapter, one of the most important factor that has prevented the development of a standard method for VE in office buildings has been the use of different definitions of VE by researchers. This situation was partially resolved with the recent introduction of different parameters defined to quantify distinct components of VE (e.g.: ε_χ, ε_a, ε_c). Because these definitions describe adequately some of the factors that affect VE in an actual space, they are currently used as a starting basis for existing and proposed standards and guidelines on VE.

Another limitation of the VE methods proposed so far resides in the difference between the results obtained and the conclusions derived by different studies following the application of the methods in test chambers. According to the review of the literature, the results of VE measurements and therefore the validity of the techniques proposed, were not interpreted in the same fashion in the 1980s and in the 1990s.

In the early 1980s, experiments performed to measure ε_a and ε_c in test chambers indicated that VE could be low enough to affect IAQ and energy conservation under some of the worst case conditions simulated (e.g.: high T_s, low q). The small number of studies of ε_a and ε_c in actual buildings however, did not allow to conclude decisively on the possible range or the magnitude of this parameter in the field. During this period, the measurement methods were mainly based on the age-of-air concept and a compartmental approach that were assumed to be reliable approaches to VE.

During 1990s, the results of ε_a measurements in office buildings and in test chambers provided further information on applicability of the methods and the expected range of VE in the field. During this period, researchers showed that VE may have been of lesser importance than was previously assumed because the values of VE measured in offices were relatively high compared to results obtained earlier for test chambers. In this latter period, which corresponds to the current state of development in the field, some authors have concluded that VE measurements using existing methods may not be applicable in the field because of the difference between actual and predicted conditions used in the models and because of the difficulty in using tracer gas techniques in the field.

These theoretical and practical limitations in VE measurement techniques indicate that there is a need for the improvement of existing techniques or the development of new techniques for VE. To improve existing techniques would require mainly the revision of the theory behind the methods as well as further testing in test chambers and in office buildings. If, the existing methods are not appropriate however, then, as some researchers have observed recently, new methods should be defined and implemented for VE. These new methods should be able to provide better and a more accurate measure of VE if they can avoid the confusion associated with existing methods and, if they can function correctly in both test chambers and in the field.

3. METHODOLOGY

As concluded in the literature review, there are several alternative approaches that can be adopted in order to improve the definition as well as the tracer gas methods developed for the measurement of VE for IAQ in office buildings. One approach identified is to continue to perform experiments in test chambers and in office buildings using the existing definitions and the existing methods related to VE (see Figure 3.1). This approach corresponds to a status quo regarding the definition of VE but the existing measurement methods could be ameliorated until they are not as limited as they are currently in their ability to evaluate VE in actual field conditions.

Another approach would be to abandon existing definitions and methods and to introduce new theories and new methods for VE that are better suited to field conditions in office buildings. Since developments in the field of building research are not concentrated uniquely on the subject of VE, this approach would require further studies to include additional parameters (e.g.: air velocities, air temperatures, building ventilation schedules, number of occupants) in the definitions of VE introduced previously.

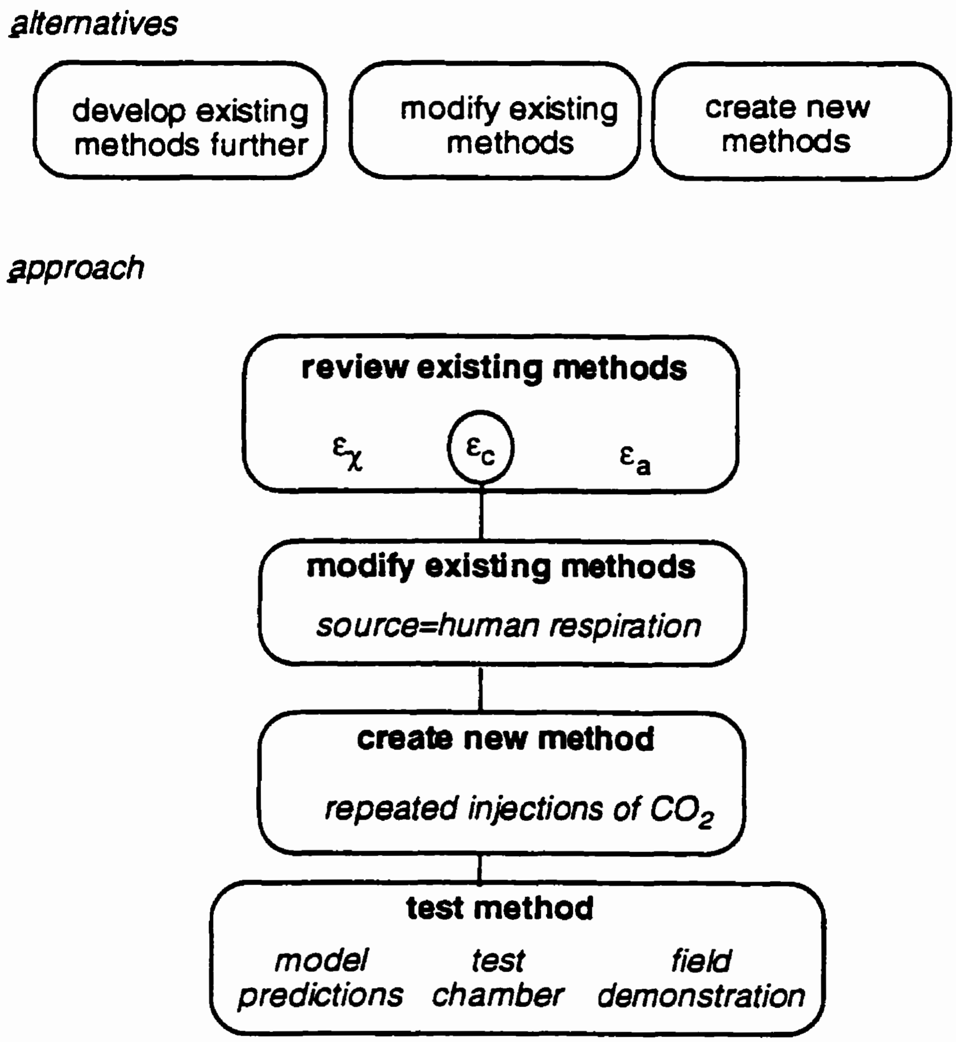


Figure 3.1: Alternatives and approach used for VE measurement

The approach selected for the measurement of VE was developed based on the existing methods used for the measurement of ε_c (see Figure 3.1). As concluded by the latest research studies [95,98,103] and as discussed in the literature review, ε_c methods currently offer the best alternative for the measurement of VE in actual buildings compared to ε_a methods. Mainly, the measurement of pollutant control using ε_c is a better index of the actual conditions experienced by office workers compared to air exchange efficiency as expressed using ε_a. Although ε_a methods are appropriate to evaluate overall room air distribution most of the existing measurement techniques are not appropriate for routine field measurements.

As mentioned earlier, current ε_c methods involve the simulation of a pollutant source of using a tracer gas. Although several pollutants have been simulated, there is not a single ε_c method that is based on the direct simulation of a source representing the human production of CO_2. Human respiration produces CO_2 along with other human bio-effluents (e.g.: VOC's) and is one of the major sources of pollutants in office buildings [21,25, 48,49,50]. Because of its importance, CO_2 was selected as the source of pollutants to be simulated for the development of the new ε_c method.

After CO_2 was selected as the pollutant source, the next step was to create a practical method that would use this gas for ε_c measurements. The approach selected consisted in using repeated injections of CO_2 at a rate equal to the human CO_2 production rate. After the method this injection scheme was created, it was tested in three different ways. First, the results from the method were predicted using the two-compartment model. Next, the method was tested in a test chamber. Finally, the method was demonstrated in an actual office building. The next sections describe the method developed as well as the tests performed to verify the performance of the method to evaluate VE in office buildings.

3.1. Description of the ε_{cm} method

The basic premise for this study was that a tracer gas could be used to simulate human respiration in a room and that the concentrations of the tracer gas could provide an indication of VE in terms of a measured pollutant removal efficiency or ε_{cm}. It was assumed that the concentrations of tracer gas around the source would vary according to the VE of the space with high concentrations of tracer gas corresponding to low VE. Based on this principle, a tracer gas was selected and an injection scheme was defined according to the normal procedure used for the development of tracer gas measurement techniques (literature). Next, the results for ε_{cm} were predicted using a two-compartment model adapted to the case of an intermittent source of pollutant.

3.1.1. Tracer gas selection

The first step in obtaining a method for field measurement of VE is to select a tracer gas that is relatively harmless and is easily detectable. As discussed earlier, of all the tracer gases currently available, CO_2 is the tracer gas that best fulfills the toxicity requirement and can be detected accurately and economically using direct reading instruments. CO_2 is also a gas recommended as an index of global room ventilation by the European and North-American standards [48,49,50]. Because of these advantages, CO_2 was identified as the best tracer gas to be used for the measurement of ε_c in the field and therefore it was selected as the tracer gas for the ε_{cm} method.

3.1.2. Tracer gas injection

The next step in the development of a tracer method is the selection of an appropriate injection scheme for the source of CO_2. An injection scheme is defined by the flow rate (e.g: L/min), the duration (minutes), and the location of the injection in the building or in a room. The value of 0.3 L/min of pure CO_2 was used for the flow of the injections since this rate represents the average CO_2 production rate of a sedentary person [49,110]. This is also the flow rate used by ASHRAE to prescribe outdoor flow rates in its ventilation standard and is therefore a recognized value for design [49]. An intermittent injection scheme using this flow rate was preferred over a continuous injection scheme. With this scheme, the source is activated for only a short period of time to avoid disturbing the background CO_2 concentrations in the room. Finally, since CO_2 is used to simulate human respiration, the injection is performed at a location in the occupied zone of the room.

3.1.3. Definition of ε_{cm} using the two-compartment model

As discussed earlier, VE was defined by comparing model predictions with actual or observed conditions (see Figure 2.1, p.15). In particular, ε_c methods were based on comparing predicted pollutant concentrations with measured pollutant concentrations in a room [90,98,100]. The same approach was used to define ε_{cm} based on the injection scheme selected for simulating human production of CO_2. The two-compartment model used to predict the concentrations obtained around a constant CO_2 source is represented in Figure 3.2 and the case of an intermittent source appears in Figure 3.3.

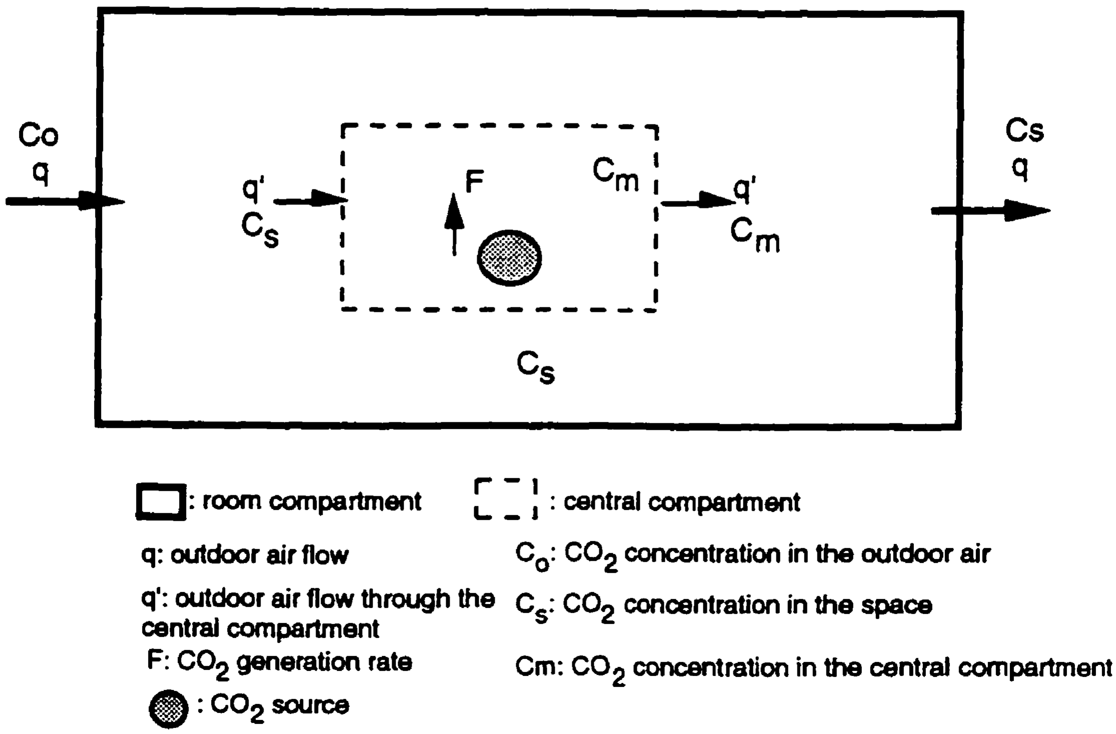


Figure 3.2: Two-compartment model

Figure 3.2 shows the two-compartment model applied to the case of a single room. The first compartment contains the whole room while the second compartment is located in the center of the room (central compartment).

If a source of CO_2 is introduced into the room, the final concentration of CO_2 is predicted using [49,88,94,110,116]:

$$Cm = Co + \frac{F}{q} \qquad (3)$$

where:	C_m:	is the measured concentration of CO_2 in the room (% or ppm),
	C_o:	is the background concentration of CO_2 in the room due to outdoor air (% or ppm),
	F:	is the amount of CO_2 generated in the central compartment (L/s, L/min),
	q:	is the outdoor air flow rate (L/s, L/min).

Expression (3) is the same as (2) described in the literature review except that C_m is used instead of C_i to represent room concentrations. In (3), C_m is equal to 0.1% (1000 ppm) for C_o at 0.03% (300 ppm) , F equal to 0.005 L/s (0.3 L/min) and q equal to 7 L/s. These values are based on the assumption that the concentrations in the room have reached a steady state and that the source of pollutant, F, and the flow rate q, are constant. This expression does not take into account the infiltration that can increase or reduce q and, it does not consider other factors such as the changes in room air temperatures and room surface temperatures. Although a more elaborate expression could be used to describe the CO_2 concentrations and therefore ε_{cm} of a room, this model is sufficiently elaborate considering the complexity of parameters affecting air flows and therefore the measurement of ε_c in the field.

A more elaborate model would include supplementary factors (e.g.: air stratification, diffuser placement) but, since these factors can not be estimated accurately, the addition of these parameters in the model would not necessarily improve the model's prediction. Additional factors such as temperatures (T) or air velocity (Va) would also complicate the measurement of ε_c because these additional parameters would have to be measured in addition to CO_2 gas concentrations. Another advantage of this model is that it is also the model used by ASHRAE [49] and therefore, the results obtained can be compared directly to the recommendations of the standard in terms of q and CO_2.

To obtain the ε_c for the room, the flow rate q in (3) was replaced by an effective flow rate, q', that corresponds to the actual flow rate within a portion of the occupied space. The expression of q' is obtained by letting [49,88,94,110,116]:

$$q' = \varepsilon_c q \qquad (4)$$

where:
- q' is the flow rate within the central room compartment (L/s, L/min),
- q is the outdoor air flow rate (L/s, L/min), and,
- ε_c is the pollutant removal effectiveness of the ventilation.

The flow rate q' into the central compartment is not a real flow but is a flow defined in terms of the efficiency of the ventilation to dilute and remove the pollutants in the central compartment. The value of q on the other hand is the actual flow rate of outdoor air in the room.

The values of q' and q can be compared to quantify the air flow distribution in each compartment and therefore the ability of the ventilation to remove CO_2 from the space. For q'=q, the conditions of mixing are the same in the two compartments and the room is fully mixed. For q'>q, the mixing is relatively better in the central compartment than for the average mixing in the room. This corresponds to a bypass of q in the occupied zone instead of a bypass of q outside of the occupied zone (central compartment). For q'<q, the mixing in the

central compartment is less efficient than the overall room mixing and the outside air does not reach the occupied zone.

The definition of ε_c is obtained by introducing (4) in (3) [49,88,94,110,116]:

$$\varepsilon c = \frac{F}{q'(Cm - Co)} \qquad (3.1)$$

According to (3.1), ε_c can be obtained if F, q', C_m and C_o are known or they are measured in the field. Ideally, if the F and q' parameters in (3.1) can be eliminated, ε_c would include only the CO_2 concentrations C_m and C_o. This would simplify considerably the evaluation of ε_c by reducing the problem to the measurement of CO_2 concentrations only.

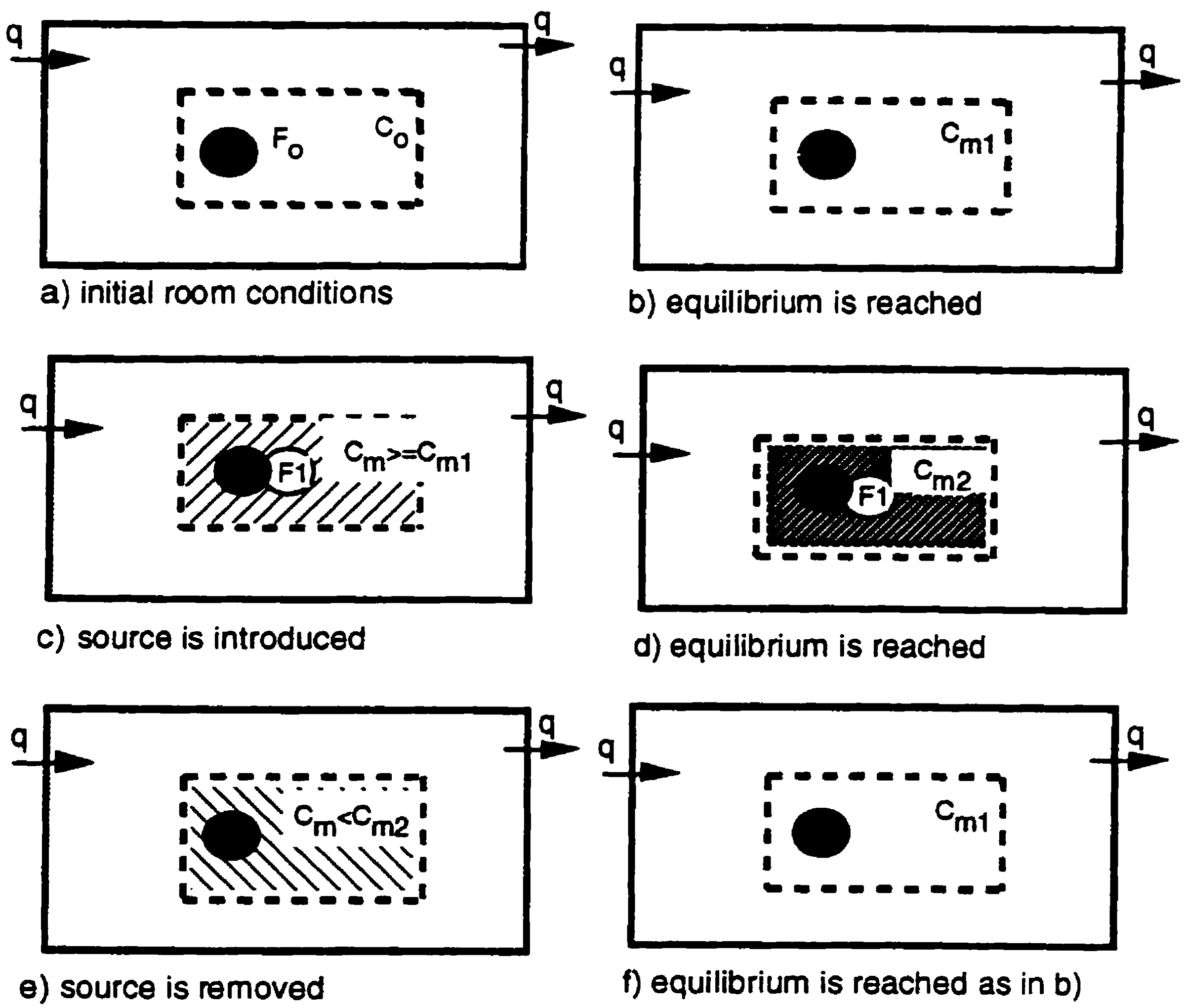


Figure 3.3: Conditions used for two-compartment model

The ε_{cm} is obtained by using the expression of ε_c in (3.1) and applying it to the case where a source of CO_2 is generated into a room as shown in Figure 3.3. Diagram a) corresponds to the case where the room is empty (e.g.: early morning) and a constant source, F_o, of CO_2 is introduced into the room (e.g.: occupants). After a period of time, the concentrations in the room will have reached an equilibrium and the concentration will reach a steady-state concentration (diagram b). This concentration will be equal to:

$$Cm1 = Co + \frac{Fo}{\varepsilon cq} \qquad (3.1)$$

where:

C_{m1}: is the measured concentration of CO_2 in the room due to background sources (% or ppm),

C_o: is the initial room concentrations of CO_2 in the room (% or ppm),

F_o: is the amount of CO_2 generated in the central compartment (L/s, L/min),

q: is the outdoor air flow rate (L/s, L/min).

When another source is introduced in the space, F_1, (diagram c), the concentrations of CO_2 in the region of the space where the source is introduced will begin to increase until an equilibrium is reached in that portion of the space (diagram d).

The concentration in d) will be equal to:

$$Cm2 = Cm1 + \frac{F1}{\mathcal{E}cq} \qquad (3.2)$$

where: C_{m2}: is the measured concentration of CO_2 in the room due to the source (% or ppm),

F_1: is the amount of CO_2 generated in the central compartment (L/s, L/min).

After the source is removed, concentrations will decrease (diagram e) until the same equilibrium conditions (background) as in b) is reached again.

The efficiency is expressed by re-arranging (3.2) to obtain:

$$\mathcal{E}c = \frac{F1}{q(Cm2 - Cm1)} \qquad (3.3)$$

Because the flow rate q is constant and because the source F_1 is emitted at a constant rate in the room, the ratio of these two values in (3.3) can be assigned a single constant value:

$$K = \frac{F1}{q} \qquad (3.4)$$

The constant K is in ppm units since F1 and q are expressed in flow rates units (e.g.: L/s, L/min). Introducing this constant into (3.3) gives:

$$\varepsilon cm = \frac{K}{(Cm2 - Cm1)} \qquad (3.5)$$

Expression 3.5 relates the efficiency to the concentrations measured before (C_{m1}) and during the injection (C_{m2}) of the tracer gas (in ppm). Expression (3.5) can be written in the following form to simplify the notation used:

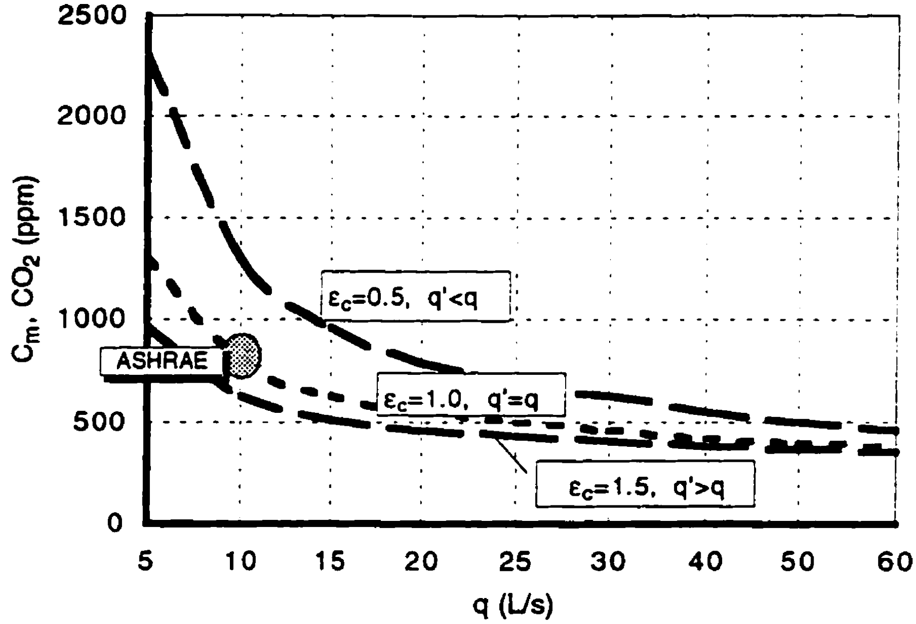
$$\varepsilon cm = \frac{K}{(Cm - Cm0)} \qquad (3.6)$$

There are several assumptions behind this expression. First, it is assumed that the air in the room can be modelled using the two-compartment model. Further, it is assumed that an equilibrium is reached in the gas concentrations in the zone surrounding the injection zone. In practice, the injection should be relatively uniform and sufficient time should be allowed to reach equilibrium. The expression is not valid if the background concentration C_{mo} is higher than the concentration C_m reached after the introduction of the source. In this case, the difference in concentrations of the denominator would be a negative value and this is an impossible situation in actual cases.

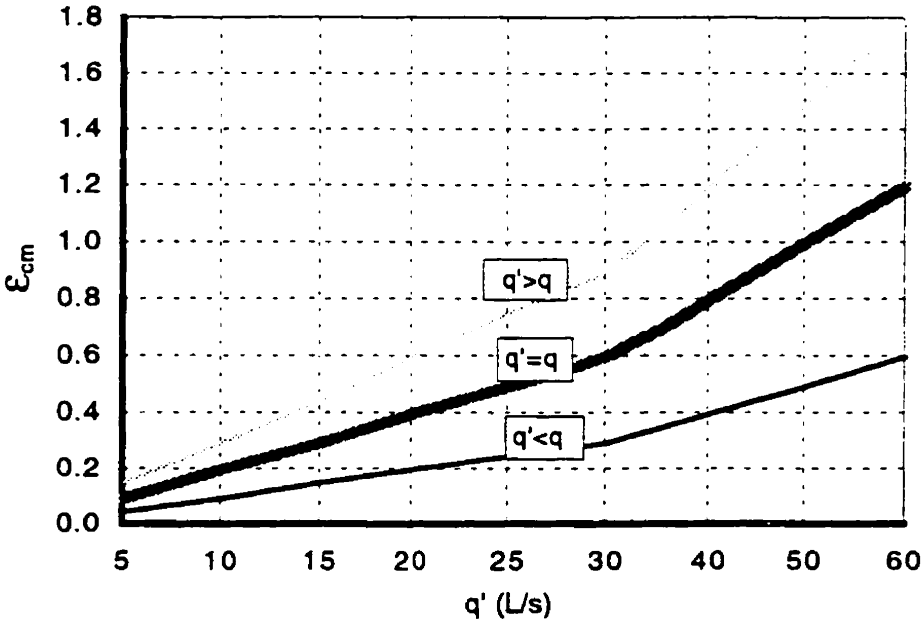
The case of maximum pollutant removal efficiency is used to assign a value to the constant K. For ε_{cm}=1.0 it is expected that C_m=C_{mo} since this corresponds to the case where all the tracer gas is removed immediately from the space (e.g.: piston flow). For this case, the value of C_m-C_{mo} in (3.6) would be zero and the efficiency would be infinite. In practice, because of the detection limit involved in the measurement of the concentrations of CO_2, a zero difference in concentrations can not be measured. Therefore, the maximum difference that is expected to be measured will depend on the detection limit of the CO_2 detector. Since the detection limit of a CO_2 detector is usually 100 ppm, K can be arbitrarily assigned the value of 100 ppm. If this value is introduced into (3.6), for ε_{cm}=1.0,

$$K = (Cm - Cmo) = 100\text{ppm} \quad (3.7)$$

The relationship between the parameters involved in ε_{cm} are summarised in Figure 3.4. Figure 3.4 a) shows the predicted C_m concentration in the central compartment of a room as a function of q and ε_c. The values of C_m are obtained using (3.2) and by setting the value of ε_c to 0.5, 1.0 and 1.5. Background concentrations of CO_2, C_{mo}, is set to 300 ppm [49]. Figure 3.4 b) shows the corresponding relationship for ε_{cm} as a function of q'. This second series of curve is obtained by introducing the values of C_m as C_{m1} and C_0 as C_{mo} in (3.6). These relationships will be used in the analysis of the results obtained using the method for the measurement of ε_{cm}.



a) C_m as a function of q and corresponding q' for three values of ε_c



b) ε_{cm} as a function of q and corresponding q' for three values of ε_c

Figure 3.4: Two-compartment model CO_2 predictions and corresponding ε_{cm}

The ε_{cm} expression in (3.6) is similar and involves the same type of approach as defined by Lidwell in the 1960s [52] and the approach recently proposed by Fisk [99]. However, contrary to these methods, this method does not involve a potentially toxic gas (e.g.: perfluorocarbons) and the tracer gas measurements can be performed using a direct reading instrument. Moreover, the definition does not require any assumptions regarding the geometry of the room.

3.2. Development and testing program

The premise that a source of CO_2 could be used to measure ε_c in office buildings was investigated according to a development (Figure 3.5) and a testing program (Figure 3.6) followed throughout the course of the study. The development program consisted of two main activities: development of a test chamber and the development of the CO_2 injection system.

Both the test chamber (labelled i to iv) and the injection schemes (labelled i to viii) have evolved during the course of the investigation. This section reviews the evolution of the method until the latest stages of development or before prototype vi and test chamber iv were used. The next sections following this review describe the test chamber and the injection systems as they were used to obtain the results presented in the remainder of thesis.

Test chamber i (64 m^3) was the same chamber used throughout the investigation but it was initially served by the university's ventilation system at that stage. In the beginning, this chamber was used to compare CO_2 and SF_6 results for tracer gas decay (n') in the middle of the room and to verify mixing conditions of the air. Therefore, there was no control over q (outdoor air flow) or T_s (air supply temperature) during the experiments. In this room, the instrumentation was for q, T_s, T_a (air temperature), V_a (air velocity) and CO_2 and

SF_6. CO_2 injections were performed by opening a CO_2 cylinder in the middle of the room.

Chamber i was also used to compare CO_2 and SF_6 decays measurement methods. Using these tests, the theoretical q of the room was estimated with a 14% error for CO_2 (2 tests) and a 4% error for SF_6, (3 tests) [153]. A 14% difference between CO_2 and SF_6 decay tests was observed. Some attempts were made to generate pulses of SF_6 and CO_2 and to evaluate the spatial distribution of SF_6 at six points in the room. These results showed that the air in the room was well mixed with one diffuser in the center and provided clues on how to improve the injection scheme (flow, duration, geometry).

Test chamber ii had an independent ventilation system and was used to improve the CO_2 injection scheme. The testing of different geometry and the frequency of the injections lead to prototype v. This prototype was a three point injection system with CO_2 injections performed at 20 minute intervals and lasting 2 minutes. The flow of injection was varied in two tests (F_1=0.3 L/min and F_1=0.1 L/min) to see if the pulses of CO_2 could be produced consistently. Results showed that a series of pulses could be generated and measured successfully using this injection scheme [154].

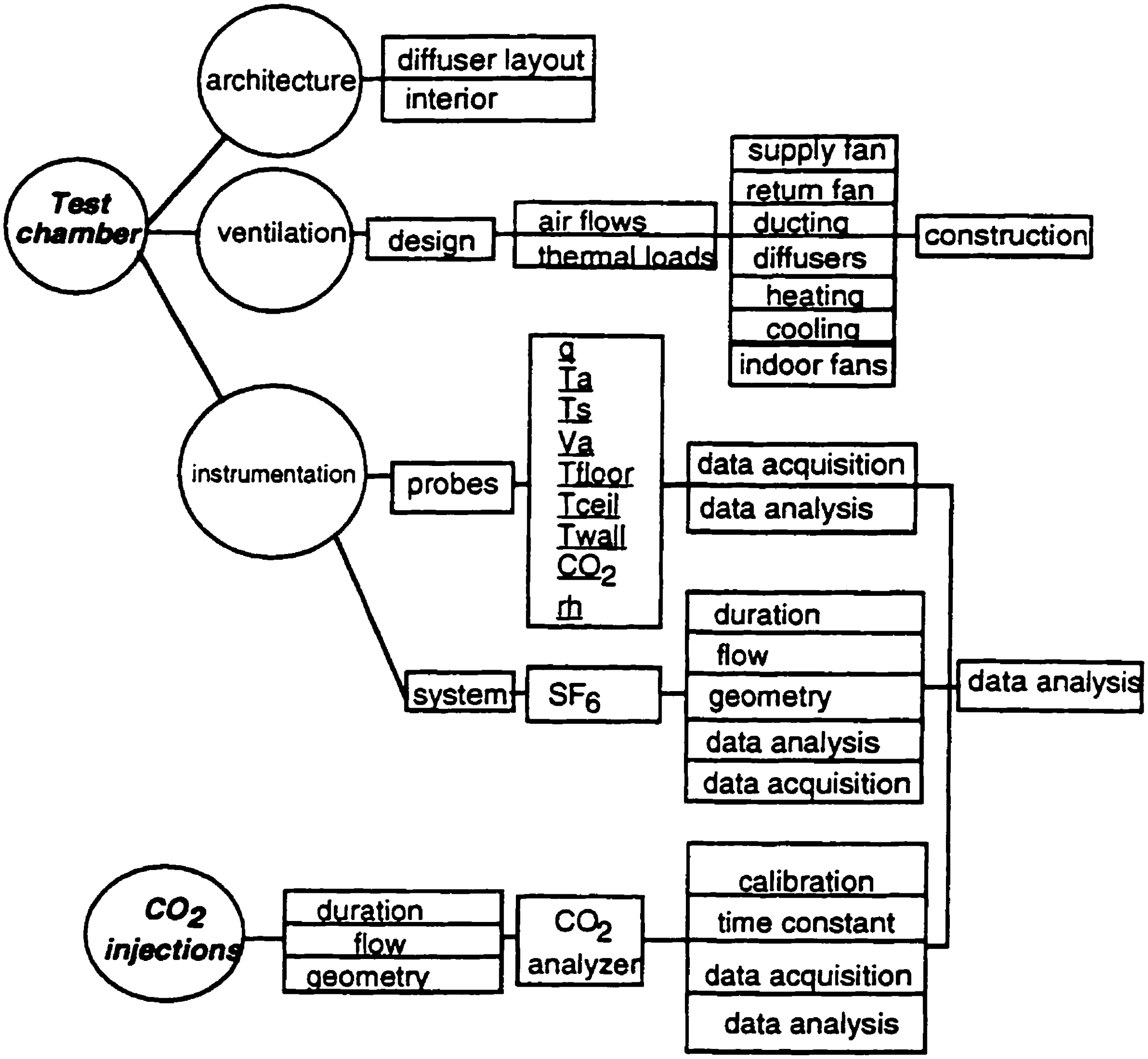


Figure 3.5: Method development program

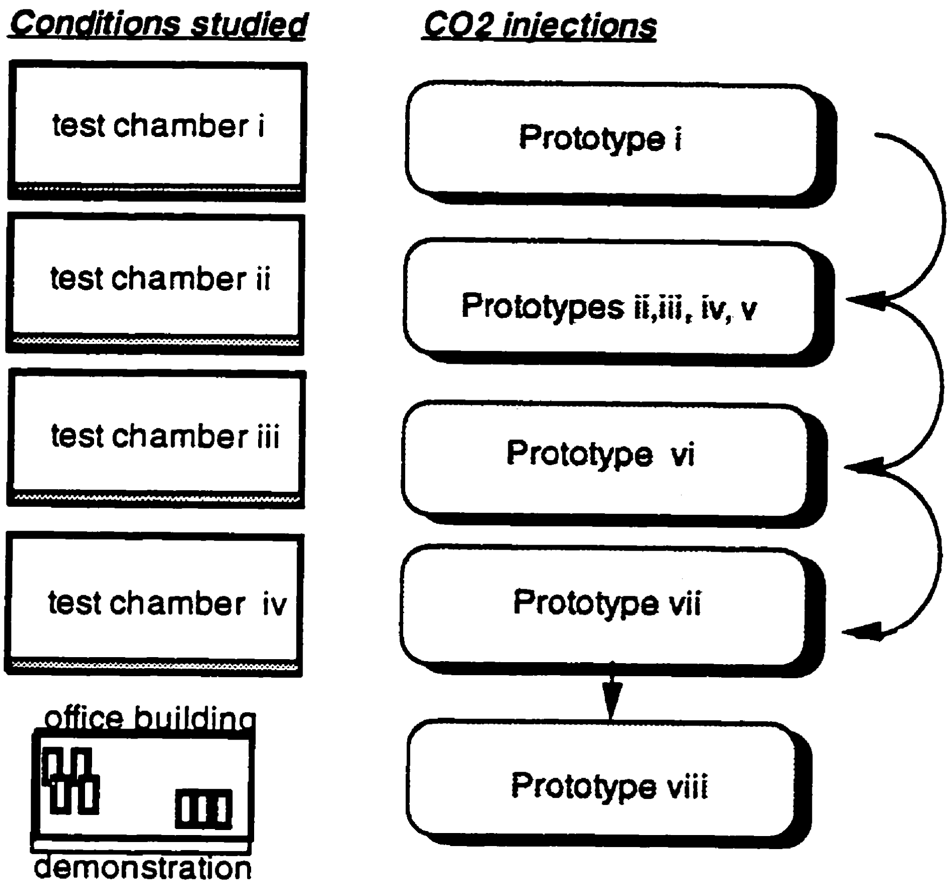


Figure 3.6: Method testing program

Test chamber iii was used to determine experimentally whether the constant K selected in the definition of ε_{cm} was correct [155]. This room had most of the instrumentation and the ventilation system present in later test chambers and the injections system (prototype vi) was also a three point injection system (4 minute injections every 20 minutes). Using two portable mixing fans in the room, it was shown that if K=100 in (3.6), ε_{cm} varied between 1.0 and 1.4 (n=9; standard deviation, sd=0.3) [155].

3.3. Instrumentation

3.3.1. Test chamber

The test chamber (version iv) constructed to test the ε_{cm} method is shown in figures 3.7 to 3.9. Table 3.1 lists the parameters measured in the room with the corresponding instrumentation, the location of the probes in the room and the sampling intervals used. Figure 3.7 shows an isometric view of the chamber with the components of the data acquisition system developed. Figure 3.8 shows a plan view of the ventilation in the room with the location of air supply diffusers, return air grille and the location of the light fixtures. Figure 3.9 shows a plan view of the room with the location of the instrumentation used for the measurement of CO_2, SF_6 and room conditions. CO_2 measurements are discussed in the next section.

This room is assumed to be typical of the size of an interior zone of an office building with a volume of 64.35 m^3 (6.5m by 3.6m and 2.75m height). It is served by a series of diffusers and returns located in the ceiling. The room was not partitioned to study only the effect of ventilation on ε_{cm}. There is no furniture in the room except for a chair on which a 100W light light-bulb is installed to simulate sensible heat gains from a human being. There are four light fixtures with a total rated power of 320W that generate most of the heat in the top part of the room. The room does not have any windows (no solar gains) and the door was locked to prevent intrusion during the tests. The walls of the room consisted of gypsum panels and the junction between the walls and the floor was sealed using aluminium adhesive tape. The walls' temperatures were not observed to be influenced by the variations in temperatures from the surrounding zones of the building.

The ventilation system for the room was designed to supply a constant q and Ts inside the room. Although it is also designed for recirculation ventilation, the system was always used with 100% outdoor air throughout the experiments conducted in the chamber ($q_{diffuser}$=q_{diff}=100% outdoor air). The system can deliver between 0 and 300 L/s of outdoor air at the diffusers by varying the speed of the air supply fan using a fan controller. According to the ASHRAE standard, for an estimated occupancy of 7 persons per 100 m^2, the minimum outdoor air flow requirement would be q=16.4 L/s for the room. The air can be delivered through any combination of the three square ceiling diffusers and the air leaves the room through a return grill located at one end of the ceiling. The installed capacity of the system was similar to the design capacity and the q and the temperatures inside the room were constant for periods of more than 4 or 6 hours depending on the season of the tests.

Diffuser flow rates (q_{dif}) were measured directly using a balometer (Airdata Multimeter, Shortridge Instruments, USA, ±5%) and the average of five readings were recorded and averaged for each flow q measured. For variable air volume tests, diffuser flow rates were estimated indirectly based on the percentage of power given to the fan. This was done using a calibration curve of q versus % power using the values of q and % fan power recorded in previous experiments. This procedure allowed q to be varied from outside of the room without disturbing room conditions.

Two portable fans (8" and 24" blades household fans) were located inside the room to provide a high mixing in the chamber and were activated from the outside. These fans were used to verify experimentally the constant K in the ε_{cm} definition and they were used to mix the air before the start of tracer gas measurements [155]. The fans were located at floor level but were adjusted to sweep the room in a periodical motion. This configuration of the fans provided a flow similar to "perfect mixing" flow as could be observed from the displacement of air using smoke tests.

Supply temperatures, T_s, were adjusted using an air-conditioner located in the outdoor air stream. The air conditioner (Carrier 300W) was used during summer tests to lower outside temperatures. In winter, the air temperature was controlled by adjusting an air control damper in the outdoor air inlet. Although supply temperatures were dependant on the outdoor air temperatures at the time of the tests, the system was able to maintain a constant T_s for several hours.

The instrumentation for the tests consisted mainly of probes for the measurement of the room conditions. These probes were connected to data-logging devices located in the room next to the test chamber. Thermocouples type K were used for room air (T_a) and surface temperatures (T_{floor}, T_{ceil}, T_{wall}) (±1°C). Surface temperatures (T_{surf}) were measured at the centre of the surfaces and the thermocouple was glued using a heat conducting paste. The room air thermocouple (T_a) was shielded against radiations using a small aluminium foil cylinder placed over the tip of the thermocouple. The supply air thermocouple was located inside the central diffuser. Another thermocouple was located outside the building to predict supply temperatures during the day and adjust the ventilation system to supply at the desired temperature. These thermocouples were connected to a data logger (Sr-006, smart-reader, distributed by CMA Progeco, Canada, ±1°C resolution) that recorded the temperature channels at intervals of 15 minutes.

Another instrument, the B&K 1213 (Bruel & Kjaer, Denmark) was used to measure T_a (±0.2°C), V_a (±5%, 0.05 to 1 m/s), Rh (±0.5 °C dewpoint), and T_{rad} (±0.5 °C) in the room at 12 minute intervals and at a height of 0.8 m above ground. The data for the 1213 were stored into the instrument's memory and these data retrieved manually after the recording period was over.

A SF_6 injection system was developed to inject the tracer gas in the supply of the ventilation and data were recorded at twelve different points in the room. The SF_6 analyser, the Bruel & Kjaer 1302, had a detection limit of 50 ppb and could take measurements every two minutes. Data for SF_6 concentrations were collected using a portable computer linked to the 1302. The SF_6 system was used mainly to measure tracer gas decay in the room and to obtain the infiltration in the room.

Data analysis programs were developed to classify and analyse the different data collected by the instruments. The data analysis programs were developed using Microsoft Excel program with macro language. These programs mainly combined all the measurements using a similar time basis. They also performed averages, maximum and minimum values calculations for the different parameters. These programs were also used to plot typical graphs of the measured parameters versus time and to study the relationship between different parameters (e.g.: ε_{cm} vs q).

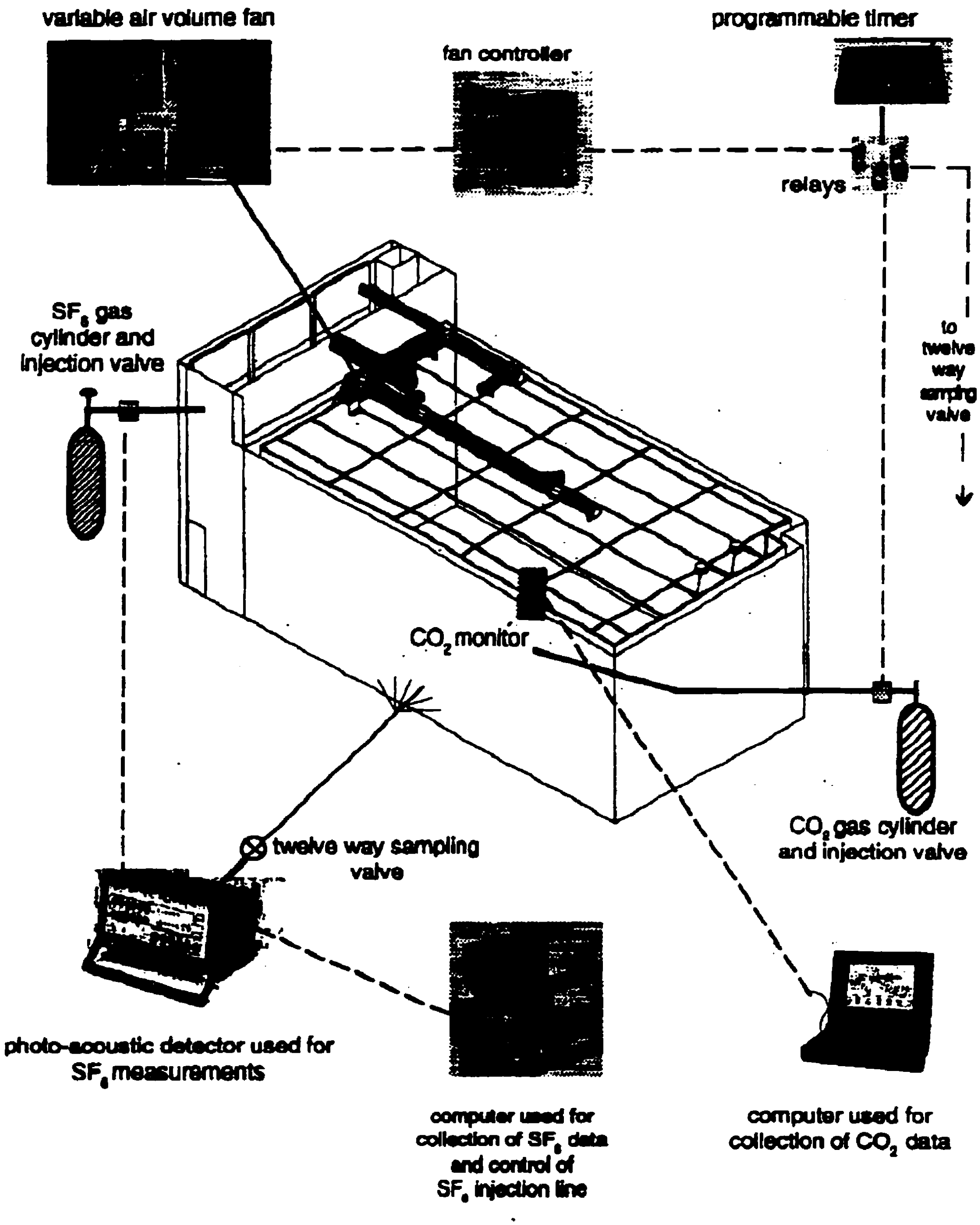


Figure 3.7: Isometric view of the room with data acquisition system

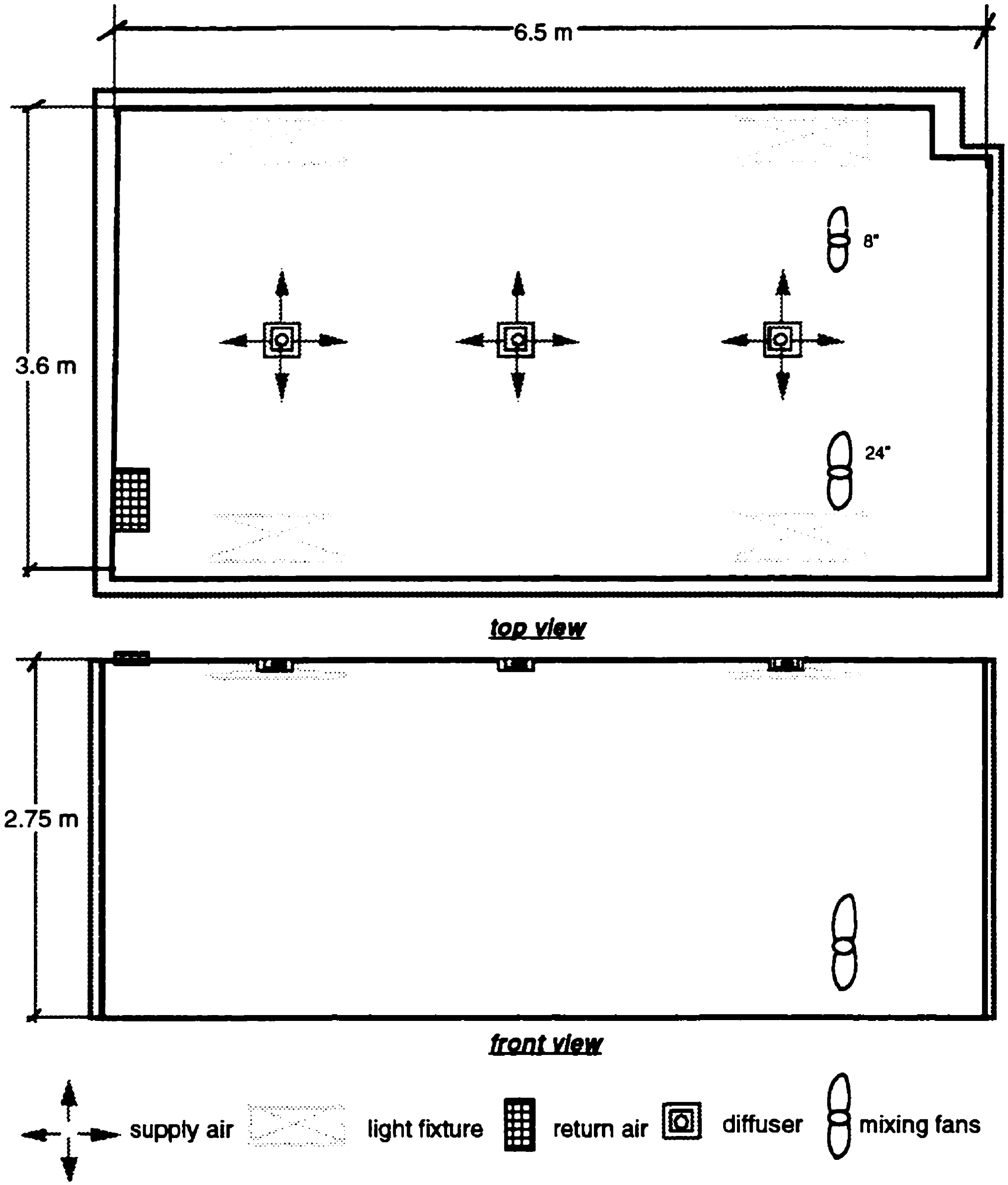


Figure 3.8: View of the room with ventilation, diffusers and light fixtures

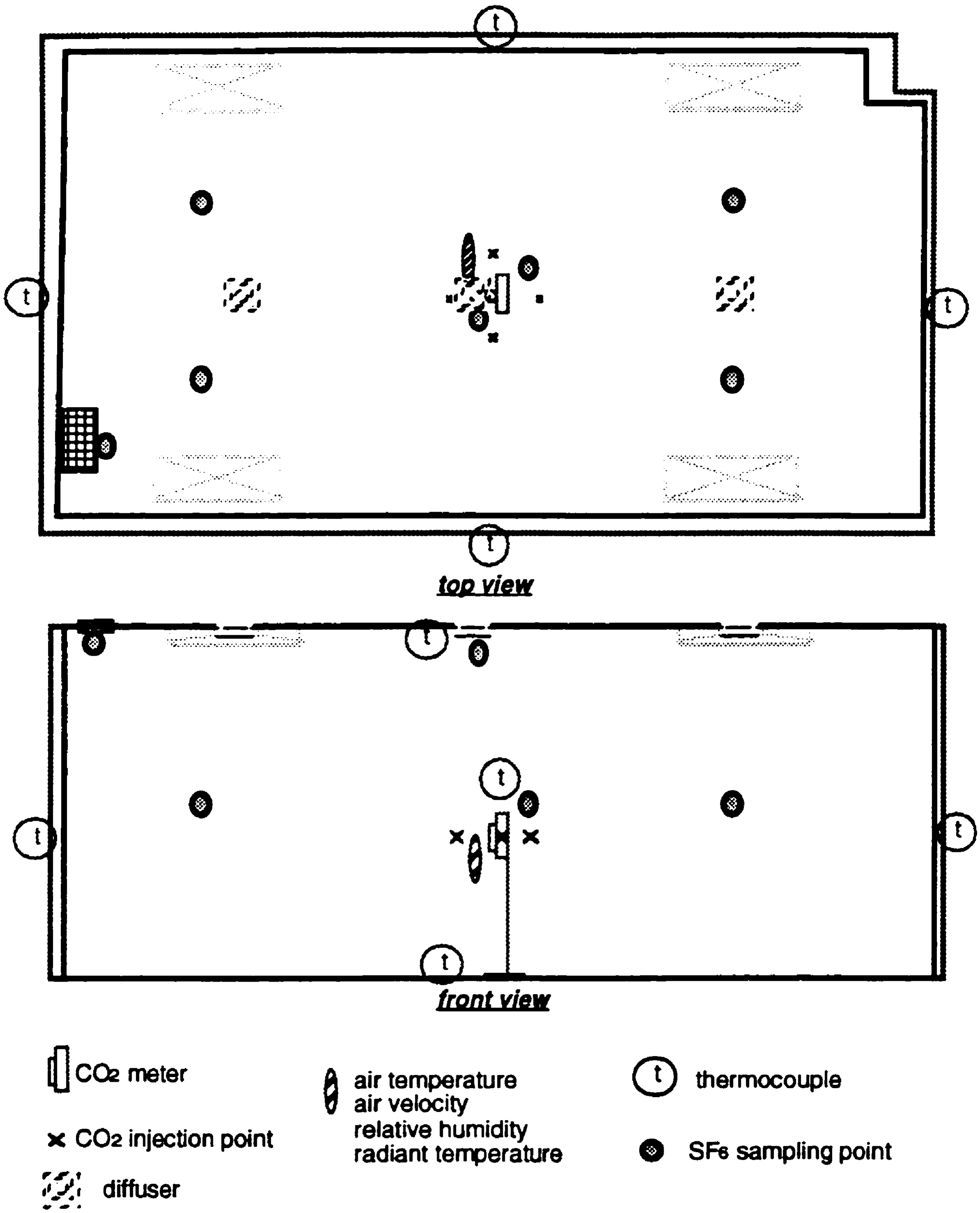


Figure 3.9: View of the room with instrumentation

Table 3.1: Parameters measured in the room

Parameter	**Instrument**	**Location**	**Sampling Interval**
Diffuser flow rate (q)	Shortridge balometer	diffuser	beginning and end of the tests
Supply temperature (Ts)	Thermocouple type K & data logger SR-006*	diffuser	15 minutes
Air temperature (Ta)	B&K♦ 1213	centre 0.9 m	6 minutes
Air velocity (Va)	B&K 1213	centre 0.9 m	6 minutes
Floor temperature (Tfloor)	Thermocouple type K & data logger SR-006	centre of floor	15 minutes
Ceiling (Tceil) temperature	Thermocouple type K & data logger SR-006	centre of floor and ceiling	15 minutes
Wall temperatures (Twall)	Thermocouple type K & data logger SR-006	four walls	15 minutes
Relative humidity (rh)	B&K 1213	centre 0.9 m	6 minutes
Radiant temperature (Trad)	B&K 1213	centre 0.9 m	6 minutes

**SR: Smart Reader*
♦B& K: Bruel & Kjaer

3.3.2. CO_2 injection system

3.3.2.1. CO_2 monitors

Two types of CO_2 monitors were used during the course of this study. One monitor was used for the effectiveness measurements (C_m) and the other monitor was used to measure background CO_2 concentrations (C_{mo}) during the field study.

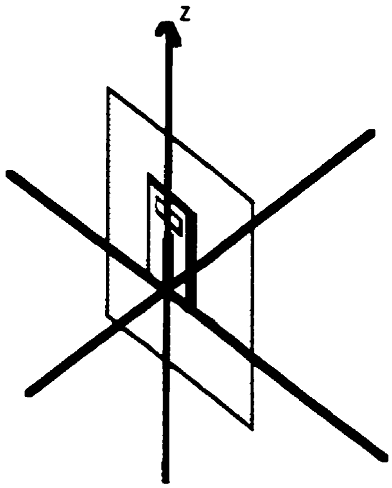
The monitors selected (model *YES-203*, Young Environmental Systems, Vancouver, British-Columbia, Canada and *PL-CO₂* from Vulcain Quebec, Canada) had a rated precision of 100 and 50 ppm respectively. Both monitors functioned by passive transport of the air around an exposed infra-red source and indicated concentrations on a scale between zero and 5000 ppm. Calibration was performed at regular intervals of 1 month or, if the monitors' span values differed by more than 100 ppm. The monitors were span calibrated using a concentration of 734 (+/-15 ppm, *Matheson* Gas cylinder) of CO_2 in air and were zero calibrated using nitrogen as specified by the manufacturer of the instruments. The data concentrations for CO_2 were recorded by the monitors at sixteen seconds (16 s) intervals.

The time response of the YES monitor was evaluated experimentally by submitting it repeatedly to two concentrations of CO_2 (400 and 734 ppm) for 20 minute intervals. The time for a 95% response (time to reach 697 ppm from an initial concentration of 400 ppm) was estimated at 144 seconds (2.4 minutes).

3.3.2.2. Injection device for CO_2 Injections

Figure 3.10 shows the injection geometry tested before the final injection schemes (vii and viii) for the method was adopted. Each of the injection geometry was tested using a smoke test followed by measurement of a series of injections in the room. The room ventilation was first set at q=0 to observe the CO_2 concentration profiles for the lowest expected range of values of q and experiments were repeated with q=40 L/s to test for a higher range of q.

The geometry of the injection was found to significantly affect the concentrations measured at the CO_2 analyser. Injection schemes i and ii did not provide uniform concentrations in time and no pattern could be observed in between injections. This type of geometry was influenced by down draft currents as was observed in the smoke patterns. Injection scheme iii and iv performed well for conditions near q but were not reliable for q at 40 L/s.



isometric view of CO_2 monitor

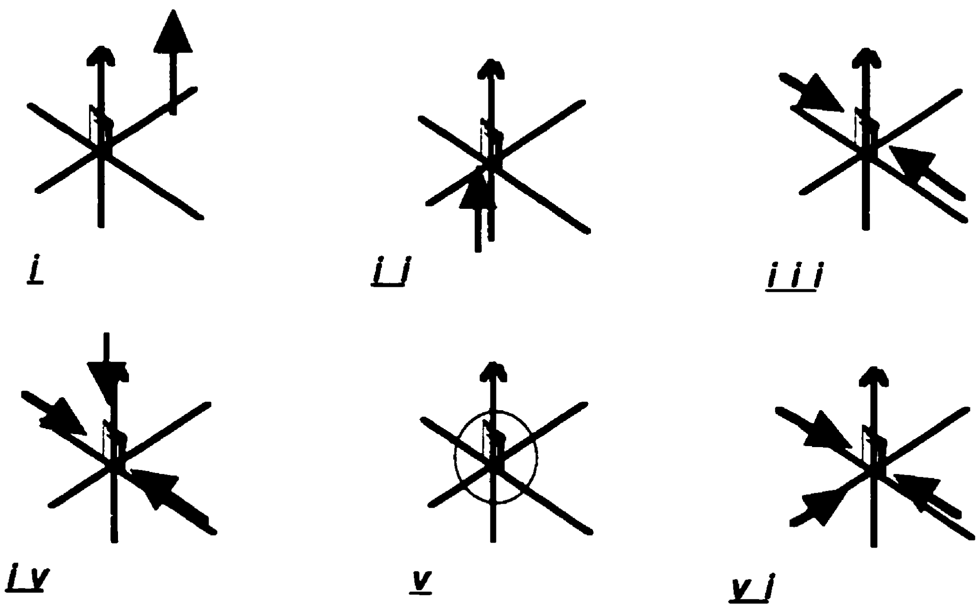


Figure 3.10: CO_2 injection prototypes i to vi (arrows represent injection points and direction)

Geometry of prototype v involved a series or equally spaced injection points located around the CO_2 monitor. Because the injection flow was distributed over more than 12 injection points, the tests showed that the gas did not reach the detector even at distances less than 15 cm. Injection geometry for prototype vi behaved well but it was finally replaced by the 4-point injection geometry used in final prototypes vii and viii.

Figures 3.11 and 3.12 respectively show a plan and a photograph of the instrument prototype (vii and viii) developed for CO_2 injections. This instrument allows the positioning of four injection points (diameter less than 2 mm) in a plane around a CO_2 monitor. To vary the sensitivity of the response of the monitor, the distances (d1 and d2) between the injection point and the face of the monitor can be adjusted.

By trial and error it was found that distances near 10 cm produced CO_2 concentrations between 1000 and 2000 ppm in the test room [154]. The height of the monitor above ground is set at 90 cm to represent a seated person.

The injections were generated by a timer opening a solenoid valve for four minutes every twenty minutes. The valve opening allowed CO_2 from a cylinder to be injected at the four injection points or nozzles. Smoke tests were used to verify that the injection was the same through all four points.

The flow of CO_2 was adjusted using the pressure of the cylinder and a rotameter (0 to 1 L/min, 0.1 L/min graduations). The rotameter reading of 0.3 L/min corresponded to an actual value of 0.36 L/min as measured using a bubble-flow meter (*Gillian*, Gilibrator model). Based on an injection over three hours, this injection rate decreased by less than 0.008 L/min/hour. Based on this test, in an eight hour period operation (three injections/per hour), the decrease in injection flow would be less than 5%.

Figure 3.13 shows a typical pulse and a sketch of the monitor response based on earlier tests [154,155,156]. Because of the delay in the opening time of the solenoid valve and the pressure variations in the CO_2 line, the injection is not a perfect pulse. The delay at the beginning of the pulse was evaluated using a video camera that filmed the displacement of the rotameter ball at 1/16 of a second interval. Following computer analysis of the individual video frames in time, the delay was found to be less than 6 seconds, introducing a 3% error with the desired pulse.

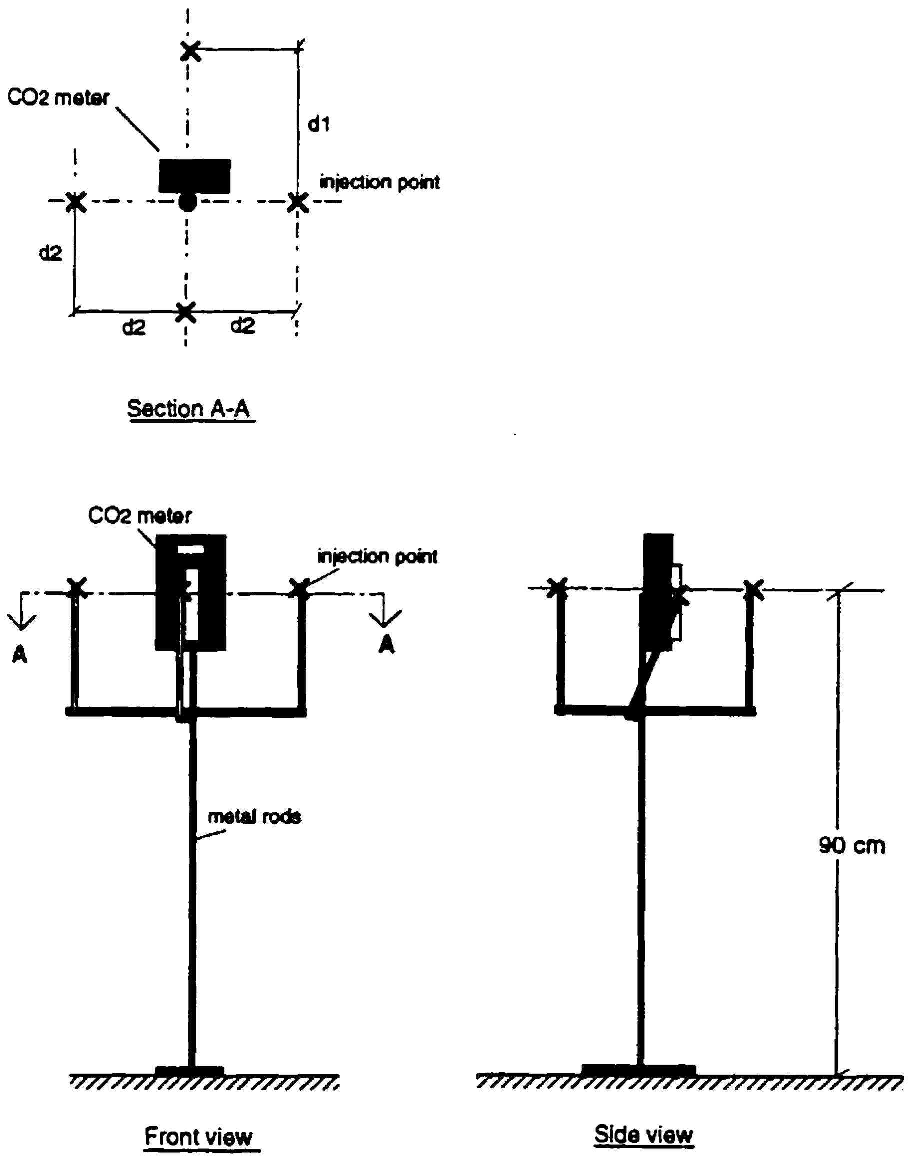


Figure 3.11: Plans of injection device developed (prototype vii)

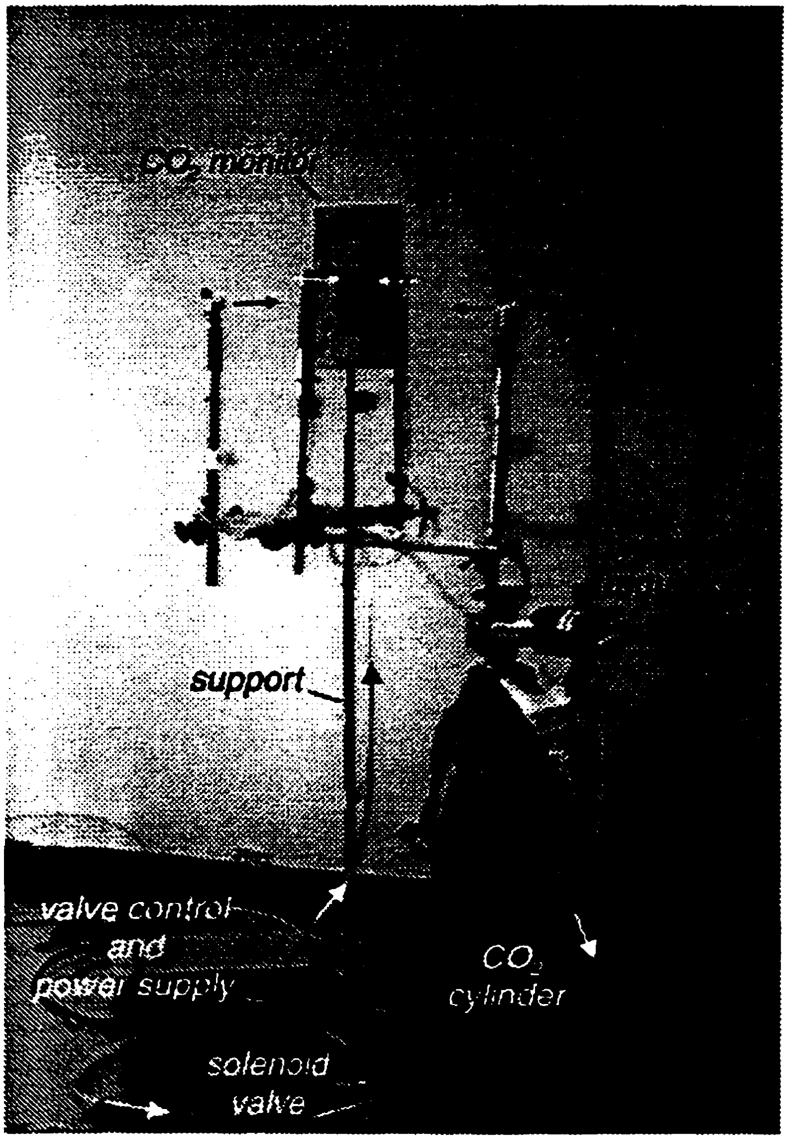
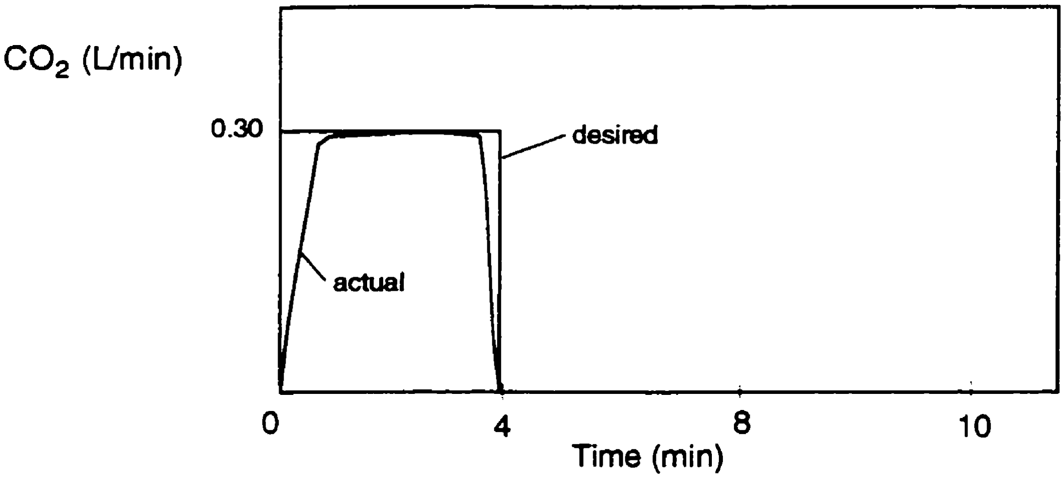
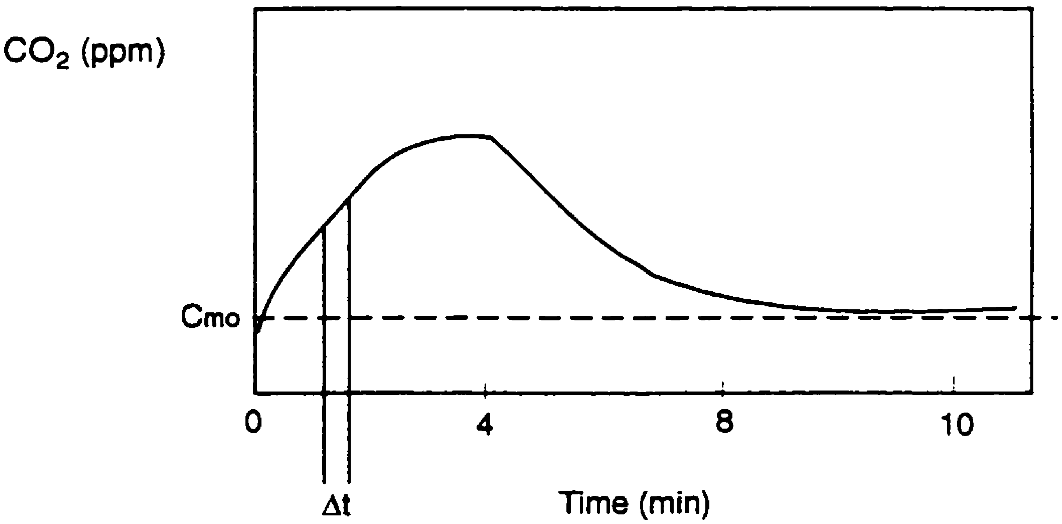


Figure 3.12: Photograph of injection device developed



a) CO2 injection



b) monitor response

Figure 3.13: Typical CO_2 injection and monitor response [154,155,156]

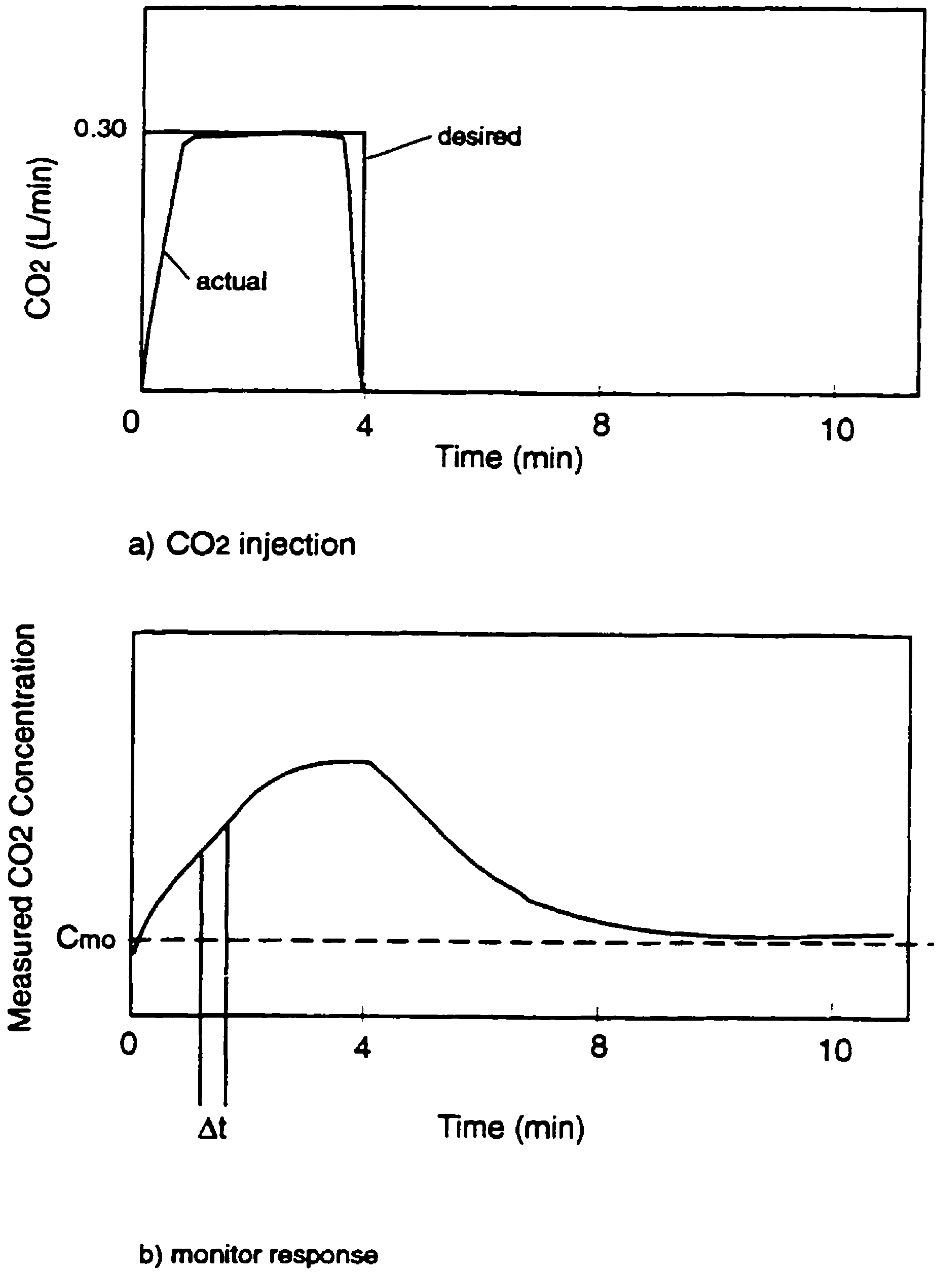


Figure 3.13: Typical CO_2 injection and monitor response [154,155,156]

3.4. Test Procedure

The ε_{cm} method was tested in the environmental chamber and a demonstration was performed in an actual office building. Chamber studies were performed with the device to evaluate the performance of the method under controlled conditions while tests performed in the office building were performed as a demonstration of the method. Tests were performed under constant diffuser flow conditions (q=constant) and, secondly, with diffuser flow varying in time (q as a function of time) in the test chamber.

For constant diffuser flow conditions, the procedure used was as follows:

1) the number of diffusers and the air flow rate (q) through the diffusers are adjusted and are measured,

2) instruments are checked and the door of the room is closed and locked,

3) the room is allowed to equilibrate for at least an hour before it is used,

4) after this equilibration period, CO_2 injections in the centre of the room are started at the same time as the data collection,

5) after an hour, the small mixing fans in the room are activated for 55 minutes and then are stopped,

6) injections continue for three hours at a rate of 3 injections/hour,

7) CO_2 injections and data collection are stopped after 6 hours.

It should be noted that the mixing fans are activated to provide a similar starting point for all experiments. The mixing period was also used to compare forced mixing conditions with the conditions obtained with the effect of the diffusers only [155]. In all the chamber tests presented later in this thesis, the injections were performed at the centre of the room. A test was failed if any of the steps in the procedure could not be completed successfully.

The procedure used for the variable air flow rate experiment was the same as that for constant q except that the diffuser flow was changed over time by a control located outside of the room. This test was performed to assess the response of the method to sudden changes in the ventilation rates.

Except for prototypes earlier than v, the CO_2 injections were performed without any operator intervention after step 4 in the procedure. The room and the data acquisition system were checked and data were saved at regular intervals during the sampling period. Experiments were performed in two shifts during 10:00 and 16:00 and between 17:00 and 23:00. Because outdoor temperatures changed more at night, experiments performed during the second shift were more influenced by outdoor temperature variations. These experiments were stored and used as a verification.

The procedure used for the field demonstration was the same as the procedure used in the chamber except that the environmental parameters were not controlled but taken as found in the building. The injection device was adapted with a portable timer and a portable power supply for the solenoid valve as well as a small CO_2 cylinder to allow its use in the field. Also, the meter was placed at desk location instead in the centre of the workspace. Concentrations of CO_2 using the second monitor (PL-CO_2) were made in the centre of the office floor as a verification. The CO_2 injections were performed without any operator intervention and the room and the data acquisition system were verified at regular intervals during the sampling period. Experiments were performed on a 24 hour basis and experimental data were saved for analysis.

3.5. Calculations

3.5.1. ε_{cm} calculations

As seen in the first section of this chapter, ε_{cm} is calculated based on the following:

$$\varepsilon cm = \frac{K}{(Cm - Cmo)} \qquad (3.6)$$

where: C_m is the measured concentration of CO_2 at the test location (ppm),

C_{mo} is the concentration at the beginning of the measurement cycles (ppm), and,

K is a constant set to 100 (ppm).

Based on the monitor response during the injection of F_1, three different formulas for ε_{cm} were defined (see figure 3.14):

(1) $$\varepsilon cm,avg = \frac{K}{(Cm,avg - Cmo)}, \qquad (3.6.1),$$

(2) $$\varepsilon cm,sum = \frac{K}{(Cm,sum - Cmo)}, \qquad (3.6.2)$$ and,

(3) $$\varepsilon cm,\max = \frac{K}{(Cm,\max - Cmo)} \qquad (3.6.3).$$

In the above, $\varepsilon_{cm,avg}$ and $\varepsilon_{cm,sum}$ take C_m as an average value while $\varepsilon_{cm,max}$ takes C_m as a maximum value during the injection.

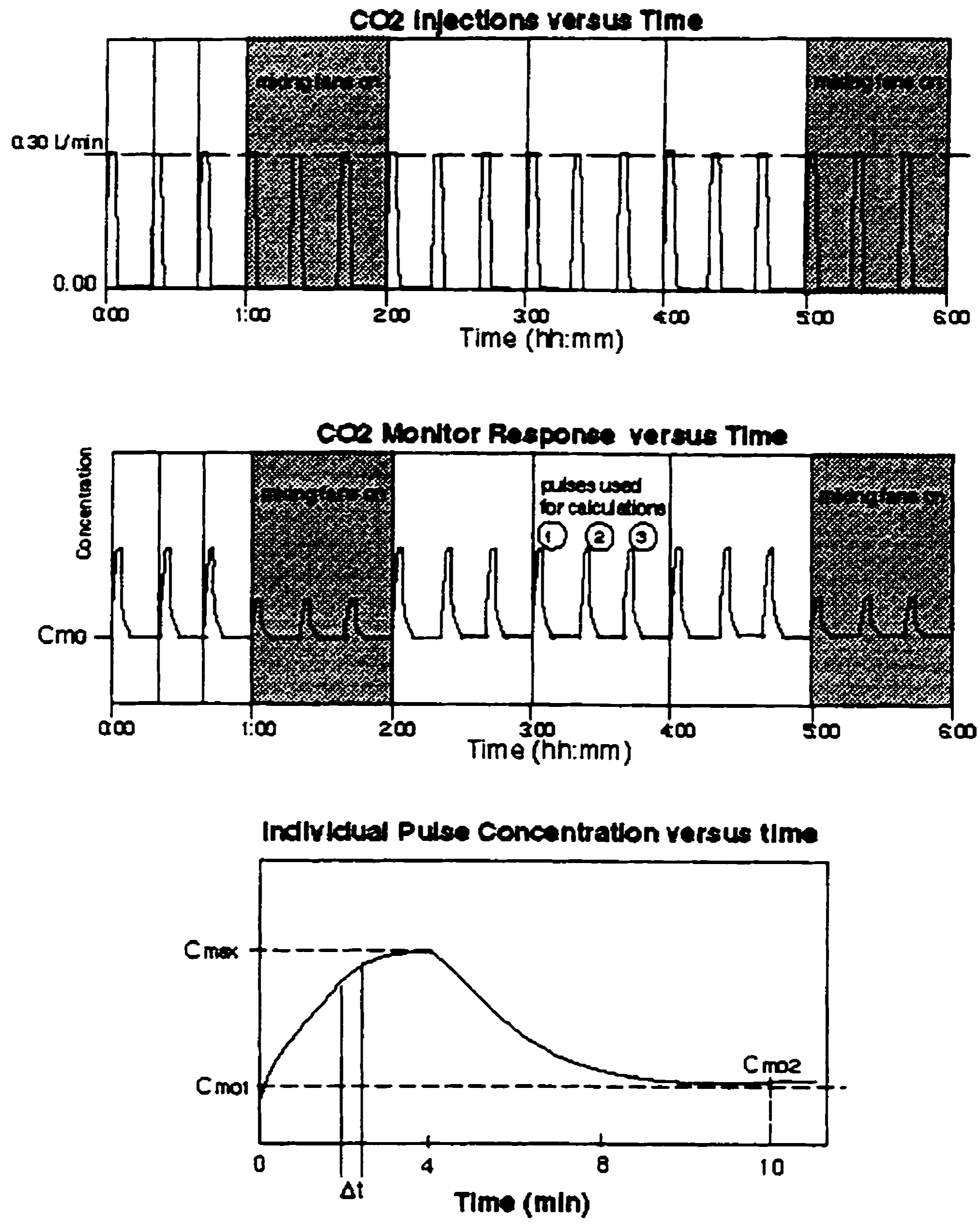


Figure 3.14: Typical data calculations

3.5.1.1. Constant term K

Based on the assumptions made on the model and following experimentation with the interior mixing fans, the constant K was set to 100 ppm [155]. In these experiments, with the mixing fans on, the concentrations measured during the CO_2 injections were maintained at an estimated 100 ppm above the room concentrations (C_{mo}≈400 ppm). This was based on the response of the monitor tested (prototype vi) in the room with q set to 40 L/s, which was more than the flow rate of 16 L/s recommended by ASHRAE for the room.

3.5.1.2. Concentrations measured during injection (Cm)

The concentration during injection was calculated using three averaging methods for the measurements. This approach was used to evaluate and compare calculation methods involving different levels of complexity.

Table 3.2: Definitions of C_m concentrations

Measured Concentration	Calculation
$C_{m,\ max}$	Maximum value
$C_{m,\ avg}$	Average concentration during ten minutes following the beginning of the injection
Cm, sum	Weighted average using the area under the concentration curve during ten minutes following the injection

3.5.1.3. Average value ($C_{m,avg}$)

The average value of the concentrations during a CO_2 injection is calculated as follows:

$$Cm,avg = \frac{\sum_{j=1}^{n} Cmj}{n}$$

where: j is the j^{th} CO_2 measurement, and,

n is the number of measurements performed.

For calculation of $C_{m,avg}$, a period of 10 minutes was used based on observation of the CO_2 concentration changes in time obtained with prototypes i to vi. For a ten minute period, with measurements every 16 seconds, n is equal to 38. For room conditions at 19 L/s (ASHRAE recommendation), it was observed that the C_m concentrations at the end of 10 minutes had reached an equilibrium [155]. The standard deviation for a typical set of measurements of ε_{cm} at 19 L/s was less than 0.04 and this corresponded to a standard deviation of less than 240 ppm for C_m concentrations [155].

3.5.1.4. Weighted average value ($C_{m,sum}$)

The weighted average value, $C_{m,sum}$, is obtained by calculating the area under the concentration curve and dividing this area by the duration of the measurements (10 minutes). The following equation is used based on the trapezoidal rule for numerical integration [151]:

$$Cm,sum = \frac{Ac}{d} = \frac{\sum_{j=1}^{n-1} \frac{1}{2}(Cmj + Cmj+1)\Delta t}{n\Delta t}$$

where:

	A_c	is the area under the concentration curve,
	d	is the duration of the measurements (10 minutes or 600 seconds),
	j	is the j^{th} CO_2 measurement,
	n	is the number of measurements, and,
	Δt	is the sampling interval (16 seconds).

The trapezoidal rule was selected over more elaborate integration methods since the time interval was relatively small thus providing relatively smooth concentration profiles over time.

3.5.1.5. Maximum value (C_{max})

The value of $C_{m,max}$ is simply set equal to the maximum concentration obtained during the ten minute period following the beginning of the injection.

3.5.1.6. Background concentration (C_{mo})

The background concentration, C_{mo}, was calculated using the average of the concentration at the beginning of the injection and the concentration measured ten minutes after the beginning of the injection.

3.5.2. Air change calculations (n')

The air change in the room was calculated based on the SF_6 decays following a uniform injection of SF_6 using the fans in the room. A linear regression over the concentrations measured was performed using the following formula [88]:

$$C(t) = Coe^{-n't}$$

where: C(t) is the concentration of SF_6 at time t,
C_o is the concentration of SF_6 at the beginning of the test,
n' is the air change rate calculated (ach),
t is the time in hours.

The concentrations at five points in the room were used to get a global measure of the air change in the room and used for the measurement of infiltration.

3.5.3. Room air mixing uniformity (U)

The uniformity of the mixing of air in the room was calculated using [104]:

$$U = \frac{\sum_{j=1}^{4} (C_{centre} - C_j)^2}{C_{centre}}$$

where: C_{centre} is the concentration of SF_6 at the centre of the room,

C_i are the concentrations of SF_6 at the other four points in the room.

The value of U was calculated using concentrations measured in the room during a ten minute period (the same as for the ε_{cm} measurements). The results were expressed in terms of a percentage if U is multiplied by 100. This index can be used as a simple index to compare ε_a and ε_c since it expresses air distribution more than pollutant removal [104].

3.6. Test Protocol

3.6.1. Chamber study

Table 3.3 shows the range of the parameters measured in the chamber during the constant flow experiments and the room arrangements used for these experiments are summarised in Table 3.4. Experiments under constant flow conditions are labelled from A to G based mainly on the type of injection performed (number of injection points and distance from the CO_2 monitor) and according to the number of diffusers supplying air into the room. For the variable q test, diffusers were configured in the same way as for the test E described in the previous section.

3.6.2. Field test

The apparatus was taken to an office building for a demonstration of its use under actual conditions of occupancy. Plans of the two offices selected for the tests are shown in Figure 3.15. One office was located on the periphery of the building and the other was located in a central zone. All diffusers were operating at constant volume and the effectiveness was measured using the injection apparatus.

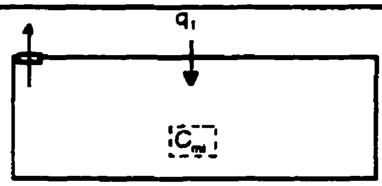
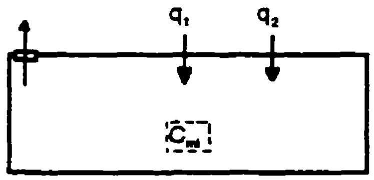
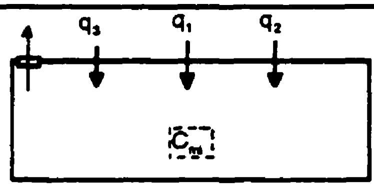
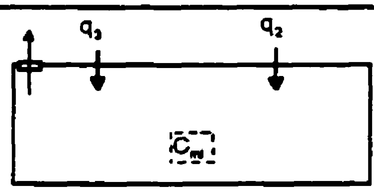
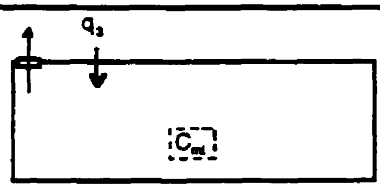
The central office received air from diffusers located in the neighbouring offices. This section was partitioned using partitions ranging from 1.3 to 1.6 m. During the tests, air velocities varied between 0.08 and 0.16 m/s. Air temperatures varied between 23.7 and 24.1 °C and relative humidities were around 15%. For the day studied, radiant temperature was the same as indoor air surface temperature this was expected since the zone did not receive any direct solar gains from windows.

The office located at the periphery (4m by 2.8 m by 2.35 m height) was ventilated by a single window diffuser at 90 L/s. The office was open to the interior of the building but was separated by a small partition (1.3 m height) from the corridor. During the tests, air velocities varied between 0.04 and 0.09 m/s. Air temperatures varied between 22.2 and 22.5 °C and relative humidities were around 20%. For the day studied, some solar gains raised the radiant temperature on the exterior wall by 2.2 °C with respect to indoor air surface temperatures.

Table 3.3: Range of parameters used during the tests performed in test chamber iv

	Test						
Parameter	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Number of experiments	4	4	28	10	4	7	3
Number of injection points	3	3	4	4	4	4	4
Injection distance d1 cm	10	10	10	13	13	13	13
Injection distance d2 cm	not applicable	not applicable	15	15	15	15	15
Total diffuser flow (q) L/S	20	0	0 to 50	26 to 85	41 to 106	26 to 85	18 to 34
Supply temperature (Ts) °C	10 to 17	not applicable	19 to 22	17 to 24	14 to 21	16 to 20	16 to 19
Air temperature (Ta) °C	20 to 22	23 to 25	23 to 27	22 to 26	20 to 23	19 to 20	19 to 21
Air velocity (Va) $x10^{-3}$ m/s	0 to 1	0 to 1	1 to 10	1 to 7	1 to 7	2 to 5	1 to 7
Floor temperature (Tfloor)°C	22 to 23	24 to 26	23 to 27	22 to 26	20 to 22	19 to 21	19 to 20
Ceiling temperature (Tceil) °C	22 to 24	24 to 27	23 to 28	23 to 27	21 to 22	19 to 22	20 to 21
Wall temperature (Twall) °C	22 to 24	23 to 27	23 to 27	21 to 25	19 to 21	19 to 21	19 to 21
Relative humidity (rh) %	9 to 22	13 to 16	6 to 52	18 to 60	20 to 25	25 to 30	26 to 27

Table 3.4: Diffuser arrangement during the tests performed in test chamber iv

Experiments	Flow Rates	Diffusers Arrangement (side view of the room)
A,B,C	$q=q_1$	
D	$q=q_1+q_2$ $q_1 \approx q_2$	
E	$q=q_1+q_2+q_3$ $q_1 \approx q_2 \approx q_3$	
F	$q=q_1+q_3$ $q_1 \approx q_3$	
G	$q=q_3$	

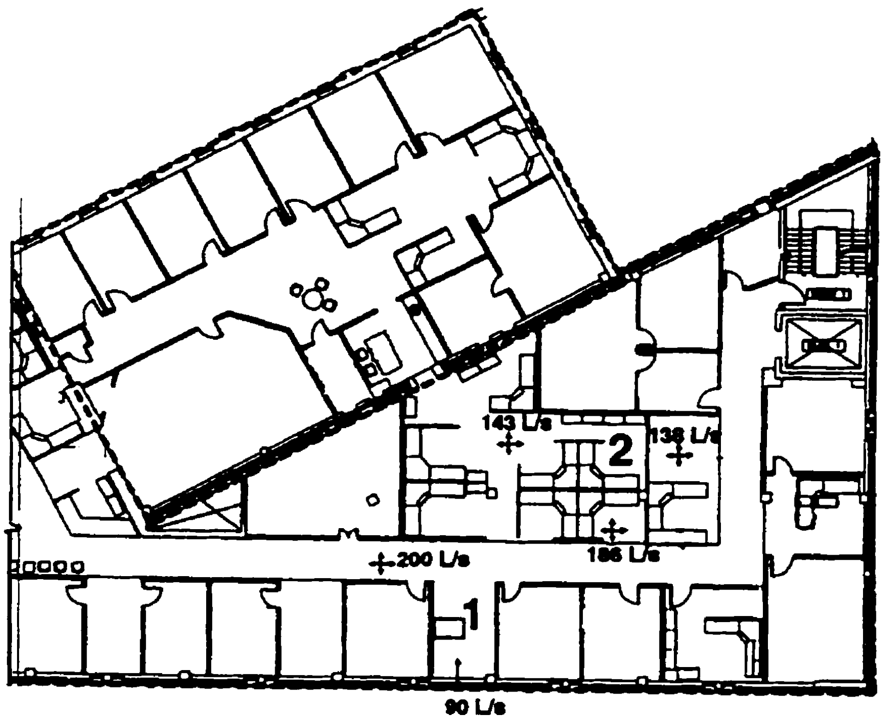


Figure 3.15: Plan of the offices studied and diffuser flows
(1: periphery, 2: interior zone)

4. RESULTS

As discussed in the last part of the literature review, there are several parameters that were expected to influence significantly the efficient ventilation or the VE of an office room. The most important parameters identified were the amount of outdoor air, q (L/s) and the air velocity, Va (m/s). Other parameters included the air supply temperature, T_s (°C), as well as the difference between air temperature, T_a (°C) and air supply temperature, ΔT_s (°C). Finally, VE was expected to vary according to the overall uniformity of the room air distribution (U) and the infiltration of air into the room (n', q=0).

Experimental results for the relationship between ε_{cm} and these room parameters were obtained in two stages (see Figure 4.1). First, early test results were obtained and used to develop and optimise the CO_2 injection device (see methodology) [153 to 156]. Next, current ε_{cm} results were obtained for an extensive set of test chamber conditions and for a field demonstration in an office building as described in the methodology earlier.

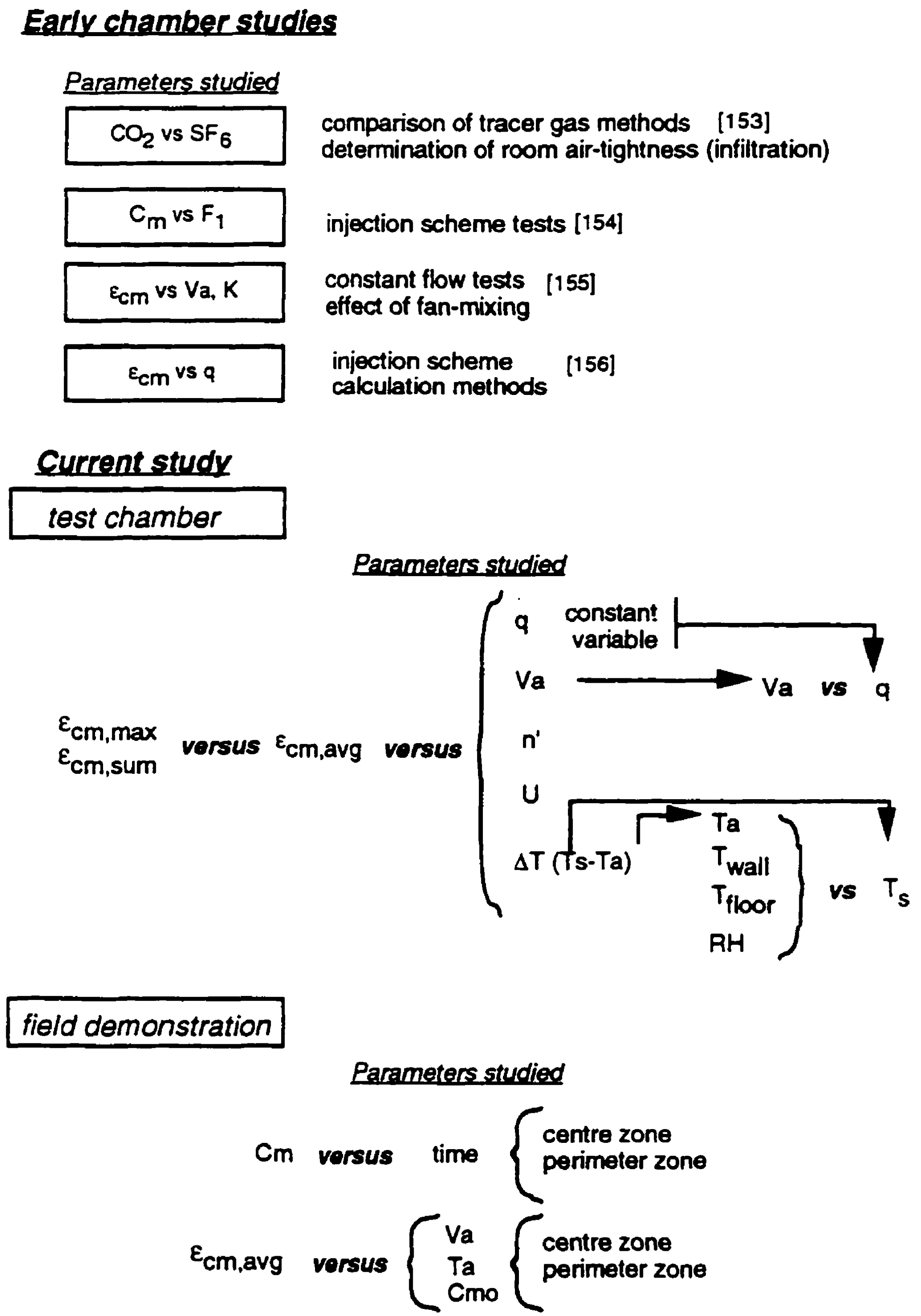


Figure 4.1: Description of ε_{cm} results presented in this chapter

4.1. Early results

The results obtained in the early phase of the research were published in three articles [154 to156][*] and a report [153]. Some of the most important results and conclusions obtained during this period of the investigation are summarised in this section.

The first set of results [153] showed how the outdoor air flow rate in the room, q, could be measured accurately using either CO_2 or SF_6 as a tracer gas. It was found that q (diffuser) could be estimated with a 5% error using SF_6 and with a 14% error using CO_2 [153] (based on tracer decay tests). This permitted to conclude that the equipment used to measure CO_2 was performing as well as the SF_6 equipment. This indicated that the test chamber was well controlled and that CO_2 results were equivalent to SF_6 results.

After these experiments, most of the work was concentrated on obtaining the correct injection prototype to measure ε_{cm}. As discussed in the methodology, it was necessary to obtain uniform CO_2 injections around the CO_2 monitor. This was achieved through a series of experiments where the tests prototypes were subjected to the room conditions typical of an office space.

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[*] These articles are reproduced at the end of this thesis

Several interesting test results were obtained using the earliest and the simplest CO_2 injection prototypes. These results showed that the uniformity of the CO_2 injections depended mainly on the number of injection points and their orientation with respect to the CO_2 monitor. After more than three injection points (irrespective of orientation) and for a distance of 10 cm (4200 cm^3), it was found that the CO_2 detector responded the best to the CO_2 injections.

After several other trials, a three point injection system (prototype iv) was found to provide consistent results when it was tested in the chamber [154]. This prototype allowed to obtain consistent patterns of CO_2 concentrations. The coefficient of variation of the method was calculated to be 20% for the normal room conditions tested in these experiments. This value indicates that, for a given room condition, ε_{cm} values are expected to vary by approximately 20% about a mean ε_{cm} value.

From these early results, it was concluded that it was possible to generate a repeated source of CO_2 under conditions of ventilation normally found in buildings. These tests also showed that the ventilation and the instrumentation of the test chamber were functioning properly. Although a three point injection produced fairly good results, the experience gained with early injection prototypes indicated cleary that the CO_2 distribution around the source was highly dependent on the geometry of the injections. After a number of trials, a four point injection system was devised. The results obtained using this prototype are presented in the next sections.

After these results were obtained, another three point injection system was developed and tested (prototype vi) [155,156]. This prototype yielded the first results on the relationship between ε_{cm} and Va [155] and between ε_{cm} and q [156]. These results confirmed experimentally that the constant K used for the two-compartment model was adequate.

4.2. Experimental results: chamber study

4.2.1. Comparison of ε_{cm} calculations

As it will be recalled, results for pollutant removal effectiveness, ε_{cm}, were treated using three types of calculations ($\varepsilon_{cm,avg}$, $\varepsilon_{cm,sum}$, $\varepsilon_{cm,max}$) as described in the methodology. Each of these calculation method used the measured CO_2 concentrations, C_m, in a different way. One calculation method was based on peak concentrations of CO_2 ($\varepsilon_{cm,max}$) measured during a CO_2 injection. The second type of calculation was based on the arithmetic average of the CO_2 concentrations ($\varepsilon_{cm,avg}$). Finally, calculations were based on the area under the concentration curves of CO_2 ($\varepsilon_{cm,sum}$) during a CO_2 injection.

The results obtained using these calculation methods are summarised in Table 4.1 and in Figure 4.2. Table 4.1 lists the ε_{cm} results obtained for the tests described in the methodology and for all three calculation methods. The data in Figure 4.2 a) show the relationship between $\varepsilon_{cm,sum}$ and $\varepsilon_{cm,avg}$ and the data in Figure 4.2 b) show the relationship between $\varepsilon_{cm,max}$ and $\varepsilon_{cm,avg}$. Each data point on the graphs is the average of three ε_{cm} results obtained during a test and this corresponds to an hourly measurement of ε_{cm} in the chamber under a constant flow rate q.

Table 4.1: ε_{cm} measurements, all cases, sorted by calculation method§

a) Maximum concentration ($\varepsilon_{cm,max}$)

Test	n	Maximum	Minimum	Average
A	4	0.29	0.12	0.17
C	23	0.97	0.03	0.25
D	8	0.21	0.05	0.11
E	3	0.08	0.06	0.07
F	7	0.08	0.05	0.07
G	3	0.10	0.06	0.08

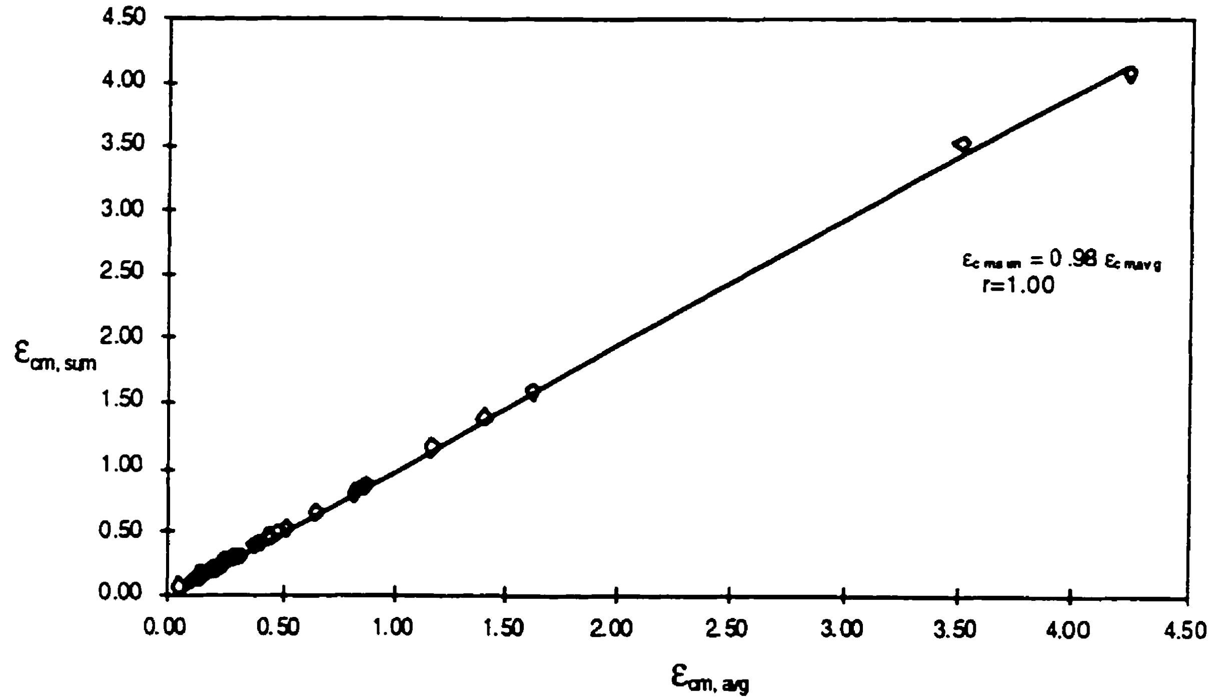
b) Average concentration ($\varepsilon_{cm,avg}$)

Test	n	Maximum	Minimum	Average
A	4	0.83	0.28	0.43
C	22	4.23	0.06	0.85
D	7	0.65	0.14	0.28
E	3	0.22	0.14	0.17
F	7	0.24	0.11	0.16
G	3	0.32	0.14	0.23

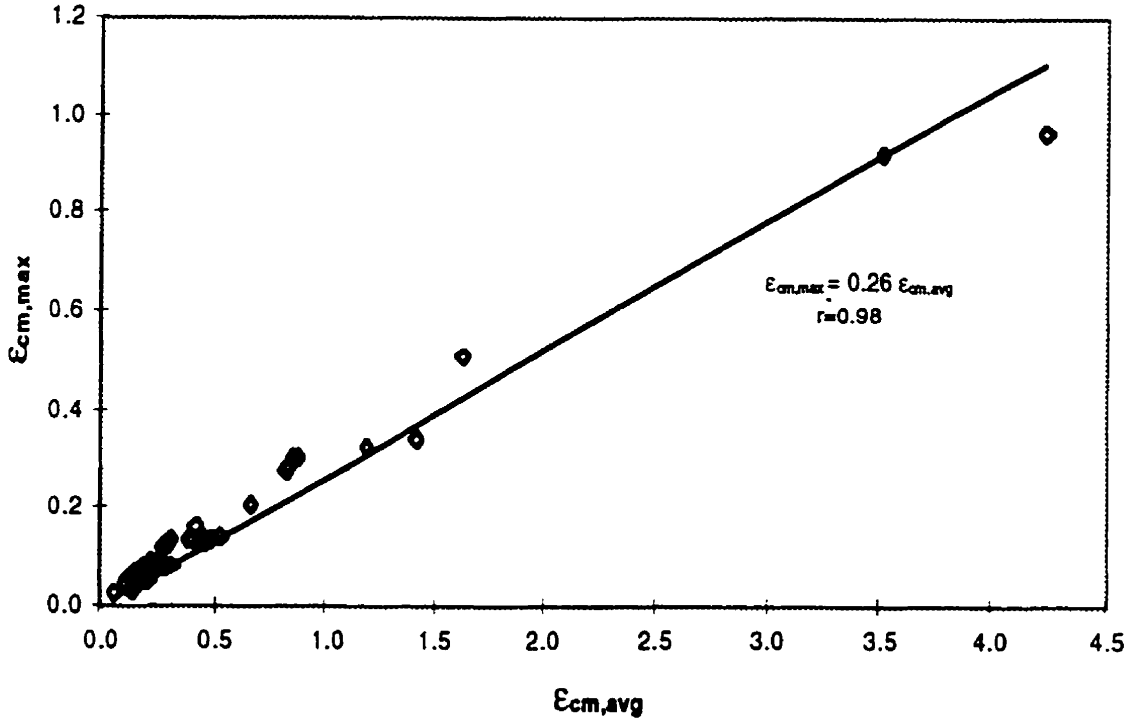
c) Summation average ($\varepsilon_{cm,sum}$)

Test	n	Maximum	Minimum	Average
A	4	0.81	0.27	0.42
C	22	4.08	0.06	0.83
D	7	0.63	0.14	0.27
E	3	0.21	0.14	0.17
F	7	0.23	0.11	0.16
G	3	0.31	0.14	0.22

§each of the results in the table is the average of three data points (hourly measurement)



a) Effectiveness, $\varepsilon_{cm,sum}$, compared to effectiveness, $\varepsilon_{cm,avg}$



b) Effectiveness, $\varepsilon_{cm,max}$, compared to $\varepsilon_{cm,avg}$

Figure 4.2: Comparison of calculation methods for pollutant removal (ε_{cm})

The average effectiveness for all three methods varied between 0.17 and 0.54 with a range of values between 0.03 and 4.23. For the same room conditions, the ε_c results calculated using $\varepsilon_{cm,max}$ were on average lower (0.17) than the values calculated using $\varepsilon_{cm,avg}$ (0.54) and the average based on calculation $\varepsilon_{cm,sum}$ (0.52).

Figure 4.2 a) and b) compares the results obtained using the three calculation methods for the experiments performed in the chamber. For each test, effectiveness calculated using $\varepsilon_{cm,avg}$ is compared with $\varepsilon_{cm,sum}$ and $\varepsilon_{cm,max}$. A linear regression on the data indicates that $\varepsilon_{cm,sum}$ was approximately equal to 0.98 times $\varepsilon_{cm,avg}$ (r=0.99) while $\varepsilon_{cm,max}$ was approximately equal to 0.26 times $\varepsilon_{cm,avg}$ (r=0.97). These relationships show that there is a very good agreement between the three calculation methods.

Since the $\varepsilon_{cm,avg}$ and $\varepsilon_{cm,sum}$ results are almost identical, either one of these expression can, in theory, be substituted for the other. Although there is a good relationship between $\varepsilon_{cm,avg}$ and $\varepsilon_{cm,max}$, the range of values of $\varepsilon_{cm,max}$ (0.03 to 0.97) is smaller compared to $\varepsilon_{cm,avg}$ (0.06 to 4.23) for the same tests. Compared to $\varepsilon_{cm,avg}$, or $\varepsilon_{cm,sum}$, results for $\varepsilon_{cm,max}$ are based only on one measurement of CO_2 every twenty minutes. Therefore, results for $\varepsilon_{cm,max}$ are expected to be more dependant on the instantaneous conditions occurring around the measurement point at the time of the measurement.

4.2.2. Measured ε_{cm} and diffuser flow rate

Because there is a good agreement between the three definitions of ε_{cm}, only the results for $\varepsilon_{cm,avg}$ are presented in the following sections. Results for the effect of q on ε_{cm} calculated using $\varepsilon_{cm,avg}$ are presented in the next two sections. The first set of results presented is for all the cases with constant flow rate (q=constant) and the second set of results is for the case of a time varying flow rate (q=variable).

4.2.2.1.Constant Flow

Results for constant flow, q, show the ε_{cm} values obtained for different constant flow rate values and for different room configurations (see methodology). The values of ε_{cm} are presented to show the relationship between ε_{cm} and q as well as the effect of the number of ceiling diffusers used to ventilate the room.

Table 4.2 presents the results of $\varepsilon_{cm,avg}$ for the cases studied in the test chamber with constant q. The table shows that the observed range of $\varepsilon_{cm,avg}$ for all cases varied between 0.06 to 1.62 with an average of 0.39. For these cases, diffuser flow rates,q, varied between 0 (infiltration only) and 101 L/s and the average diffuser flow rate was 31 L/s. Temperature and relative humidity during these tests were reported earlier in the test protocol section of the methodology.

Table 4.2: $\varepsilon_{cm,avg}$ for constant q, all cases†

		$\varepsilon_{cm,avg}$			q (L/s)		
Test	n	Maximum	Minimum	Average	Maximum	Minimum	Average
A	4	0.83	0.28	0.43	19	19	19
C	20	1.62	0.06	0.54	36	0	17
D	6	0.65	0.14	0.30	69	25	44
E	3	0.22	0.14	0.17	101	57	79
F	7	0.24	0.11	0.16	80	25	49
G	3	0.32	0.14	0.23	32	17	24
all	43	1.62	0.06	0.39	101	0	31

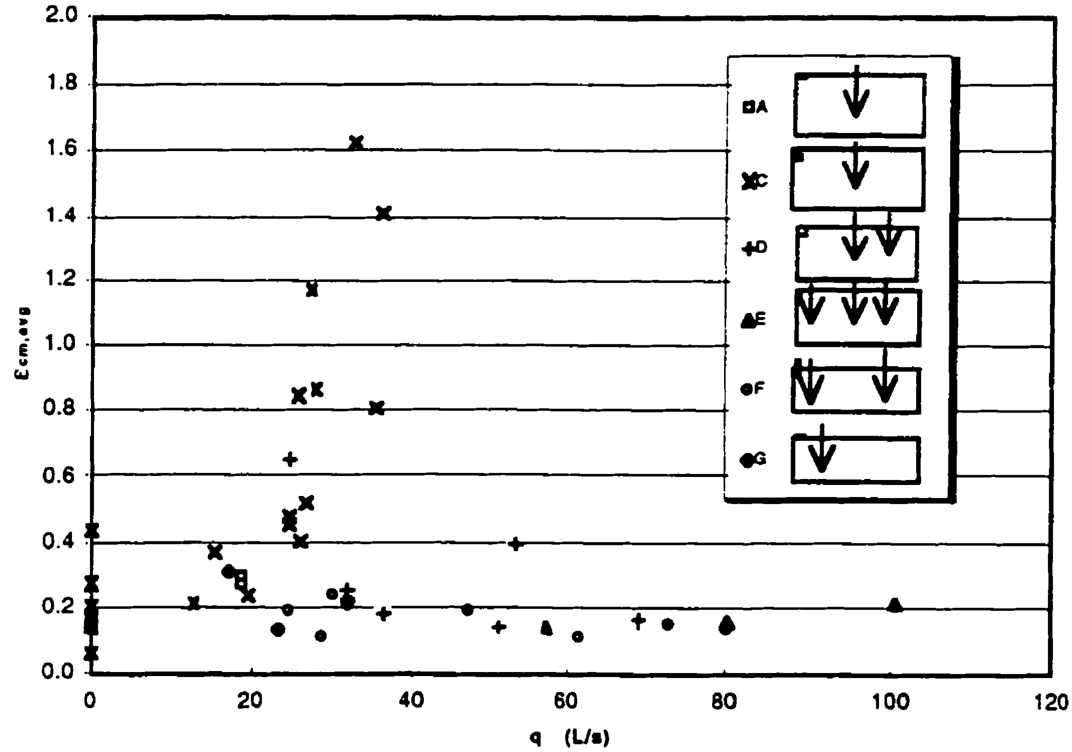
†each of the results in the table is the average of three data points (hourly measurements)

Figure 4.3 shows $\varepsilon_{cm,avg}$ as a function of diffuser flow rate, q, for the tests presented in the table. Figure 4.3 a) shows the results for $\varepsilon_{cm,avg}$ for all the cases and, figure 4.3 b) shows the results for test C only. Test C was selected because the experiments in this category were designed specifically to study the relationship between diffuser flow and $\varepsilon_{cm,avg}$. The other experiment types used much higher flows than the recommended ASHRAE of 16 L/s (D,E,F) or involved a different injection scheme (A, B). The effect of infiltration on the q values near zero flow and the effect on ε_{cm} values is discussed later in this chapter (p.152) with the results of SF_6 measurements.

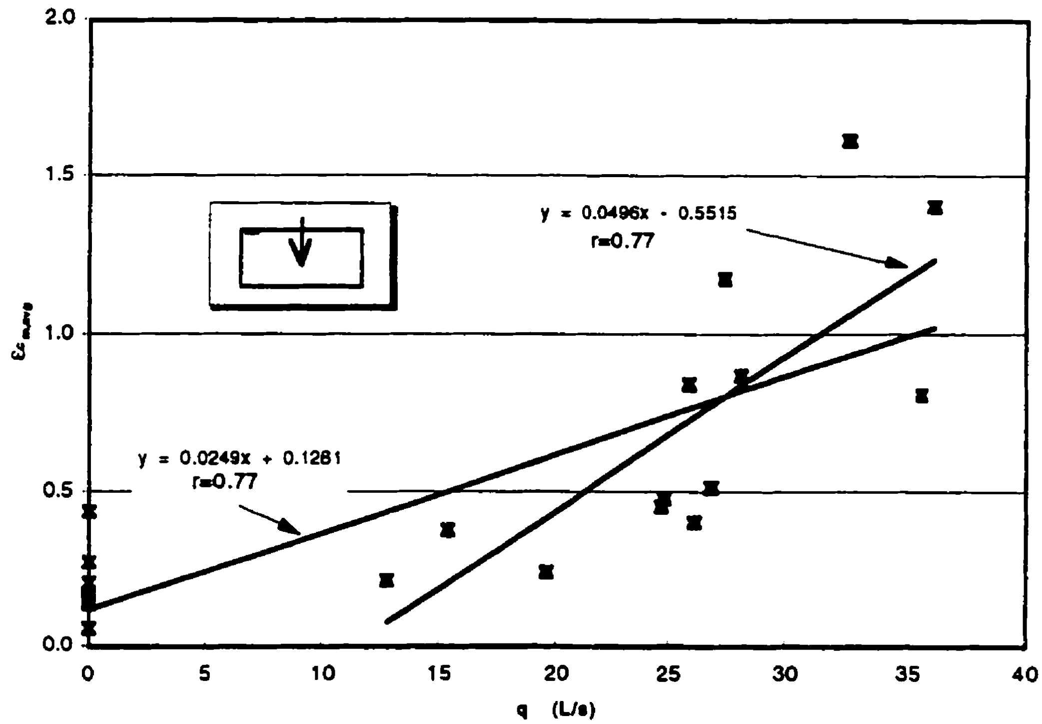
Figure 4.3 a) shows $\varepsilon_{cm,avg}$ as a function of q for all the cases of diffuser arrangements studied. Overall, effectiveness results for the test performed concentrate in three zones. The first zone is for q below 10 L/s or near zero, the second zone is for q between 10 and 40 L/s and the last zone is for q greater than 40 L/s. For q near zero and q above 40 L/s effectiveness were all measured below 0.5 while for q between 10 and 40 L/s, $\varepsilon_{cm,avg}$ varied between 0.10 and 1.6. For diffuser arrangements tests A and C (one central diffuser), the measurements show an increase in ε_{cm} with q. For test D (two diffusers), ε_{cm} decreased between 25 to 30 L/s but remained constant above this range. For test E and F, ε_{cm} remained below 0.5 over all the range of the experiments.

Figure 4.3 b) shows the change in $\varepsilon_{cm,avg}$ for q between 0 and 40 L/s for test C only. For values of q of near zero (infiltration only), $\varepsilon_{cm,avg}$ varied between 0.06 and 0.4 with an average of 0.21. For q between 10 L/s and 36 L/s, $\varepsilon_{cm,avg}$ increased from 0.2 to 1.6 in proportion to the diffuser flow rate (r=0.77).

The relationship between $\varepsilon_{cm,avg}$ and q can be approximated by a regression line for the lower end (q<10 L/s, infiltration only) or the higher range of q (q>10 L/s, no infiltration) tested. The coefficient of linear corellation for both ranges of flows is the same (r=0.77) but the slope of the lines and the intercepts are different. If the lower end of the flows is included in the analysis, ε_{cm} increases by 0.25 per 10 L/s and ε_{cm} has a minimum of 0.12. If only the higher range is considered, ε_{cm} increases by 0.50 per 10 L/s and ε_{cm} has a minimum of 0.55 as determined by the regression line. The results for $\varepsilon_{cm,avg}$ as a function of q are discussed further in the next section where results for a varying flow rate are presented.



a) $\varepsilon_{cm,avg}$ as a function of q for all chamber tests



b) $\varepsilon_{cm,avg}$ results for q between 0 and 40 L/s for test C only

Figure 4.3: $\varepsilon_{cm,avg}$ versus q, q=constant

4.2.2.2. Variable air volume q

As described in the methodology, the variable air volume test was designed to obtain experimental results on the effect of a varying flow rate q on pollutant removal effectiveness, ε_{cm}. For this experiment, the room was equipped with three diffusers as in the category E experiments. Also, for this test, room temperatures were held constant. The supply temperature, T_s, was set at 15°C and the resulting air temperature T_a was constant at 22°C. These conditions were maintained while the flow rate, q (100% outdoor air), in the room was changed in time and ε_{cm} was measured.

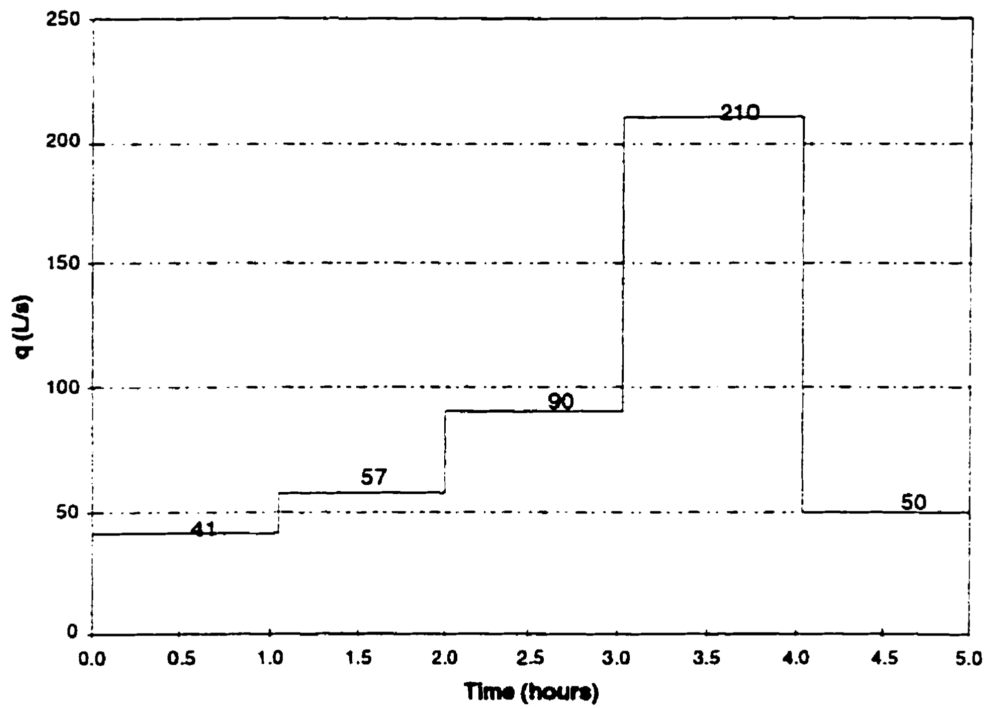
Figure 4.4 a) shows how the flow rate was varied every hour in the room. The corresponding CO_2 concentrations measured using the injection device are shown in figure 4.4 b). Flow rates were varied between 41 and 210 L/s at one hour intervals. The corresponding CO_2 concentrations measured varied between background concentrations (C_{mo}=460 ppm) and a maximum concentration for each pulse (1300 $<C_{max}<$1500 ppm). Observation of the CO_2 concentration profile and particularly the peak concentrations indicate that the changes in concentrations in time follow the changes in q. The response is dampened in time and there is a lag between the CO_2 concentration response and the changes in q. This response was also observed for tests conducted with earlier injection prototypes.

Figure 4.5 shows the time variations of $\varepsilon_{cm,avg}$ and ε_{cm} as a function of time and diffuser flow rate. !n figure 4.5 a) values for $\varepsilon_{cm,avg}$ are shown for every hour and values for ε_{cm} for every 16 seconds. The values of $\varepsilon_{cm,avg}$ were calculated using one CO_2 pulse instead of three as defined in the methodology. Results for $\varepsilon_{cm,avg}$ are therefore 10 minute averages instead of hourly averages. The ε_{cm} values calculated (dotted lines) are obtained by substituting each CO_2 concentration measurement into the ε_{cm} calculation formula. This generated instantaneous values of ε_{cm} that represent the "envelope" or the contour of the ε_{cm} variations during the CO_2 injection period.

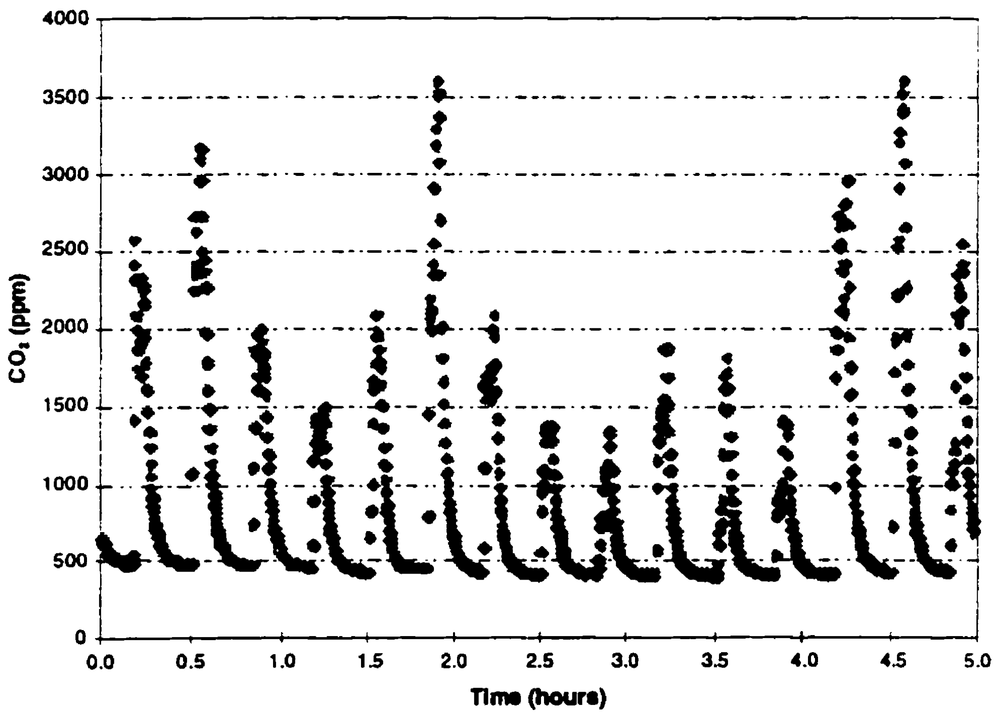
Figure 4.5 b) shows $\varepsilon_{cm,avg}$ as a function of diffuser flow rate (q). In figure 4.5 b), $\varepsilon_{cm,avg}$ varied between 0.08 and 0.28 with q varying between 41 and 210 L/s. Average values of $\varepsilon_{cm,avg}$ were 0.10, 0.08, 0.11, 0.21 and 0.21 for flow rates of 41, 50, 57, 90 and 210 L/s respectively. In comparison, for a constant q (previous section) $\varepsilon_{cm,avg}$ for case E (same number of diffusers) varied between 0.14 and 0.22 for q varying between 57 and 101 L/s.

Based on the observation of the distribution of the results, the relationship between $\varepsilon_{cm,avg}$ and q can be approximated by a regression line for two ranges with q< 100 L/s and q>0 L/s. The correlation coefficient for the first range of q (r=0.75) is higher than the coefficient for the whole range of q (r=0.66). Given the variability of the method (20%) these results show that ε_{cm} can be predicted fairly well using q (variable) over both of these ranges.

The correlation coefficients obtained under variable q (r=0.66 to 0.75) are slightly lower than the coefficient obtained for constant q tests (r=0.78). The difference is small however considering that room conditions were not the same and that flow rates were not constant in the first case. These results and the results from the preceding section clearly indicate that, the ε_{cm} was directly dependent on the diffuser flow rate for the conditions simulated in the test chamber.

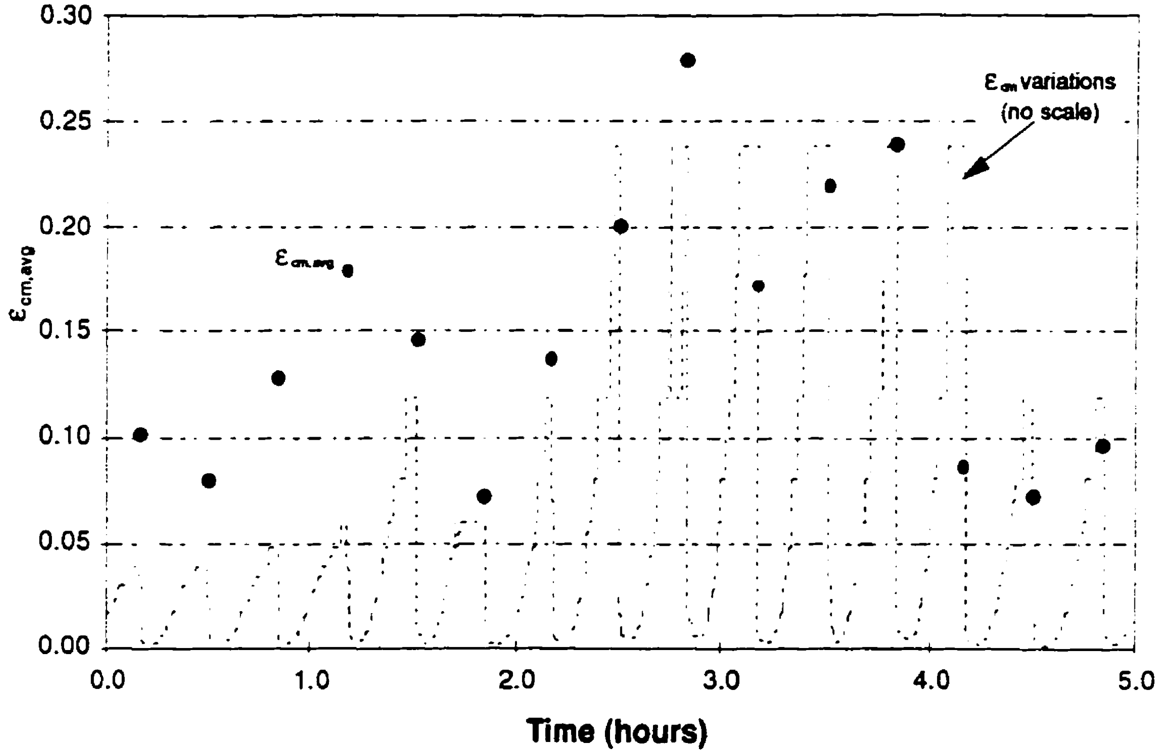


a) diffuser flow rate (q) in time

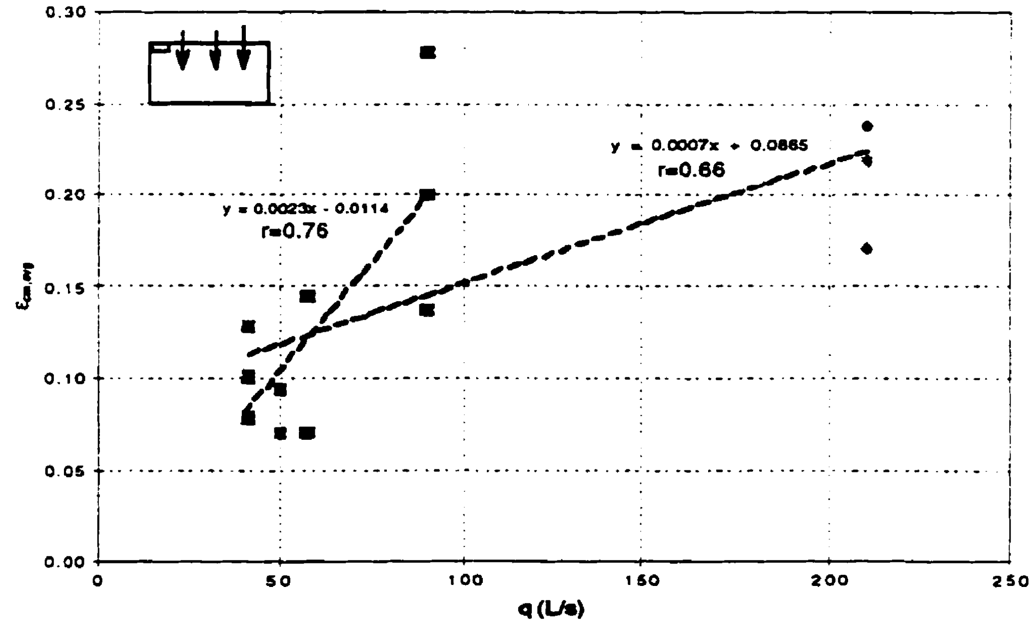


b) CO_2 concentrations at injection point

Figure 4.4: Results of CO_2 measured with diffuser flow (q) varying in time



a) effectiveness ($\varepsilon_{cm,avg}$) as a function of time



b) effectiveness ($\varepsilon_{cm,avg}$) as a function of diffuser flow rate(q)

Figure 4.5: Effectiveness in time and as a function of diffuser flow rate

4.2.3. ε_{cm} and air velocities (V_a)

As described in the methodology, air velocity measurements, Va, were made next to the CO_2 injection device in the center of the room. The pollutant removal effectiveness results obtained using ε_{cm}, were expected to be strongly influenced by the air velocity Va around the source.

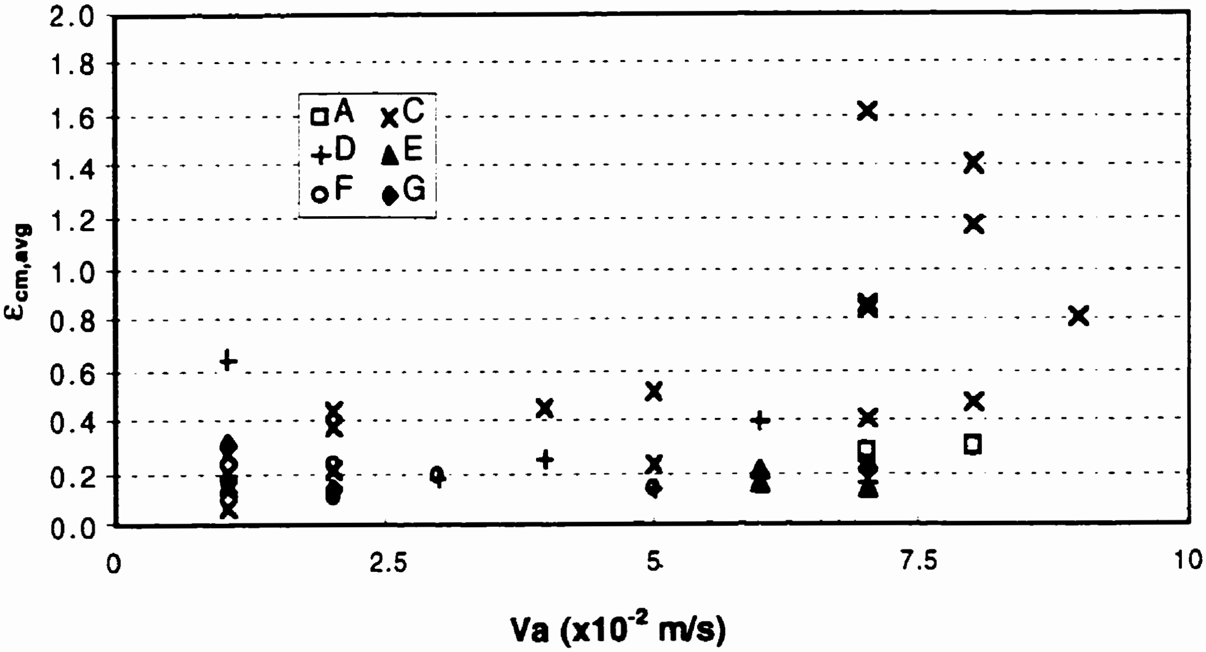
Table 4.3 presents the results of ε_{cm} and air velocities (V_a) for the cases studied in the test chamber. The ε_{cm} for all cases varied between 0.06 to 1.62. with an average of 0.40. The corresponding for air velocities varied between 0.01 and 0.09 m/s and an average of 0.05 m/s.

Figure 4.6 a) shows $\varepsilon_{cm,avg}$ as a function of air velocity, V_a, for the cases studied. Figure 4.6 b) shows the results for $\varepsilon_{cm,avg}$ for all the cases and, in b) results for test C are shown. As indicated previously, test C is selected because these experiments were designed specifically to study the relationship between ε_{cm} and q and therefore, they can also be used to study the relationship between ε_{cm} and V_a.

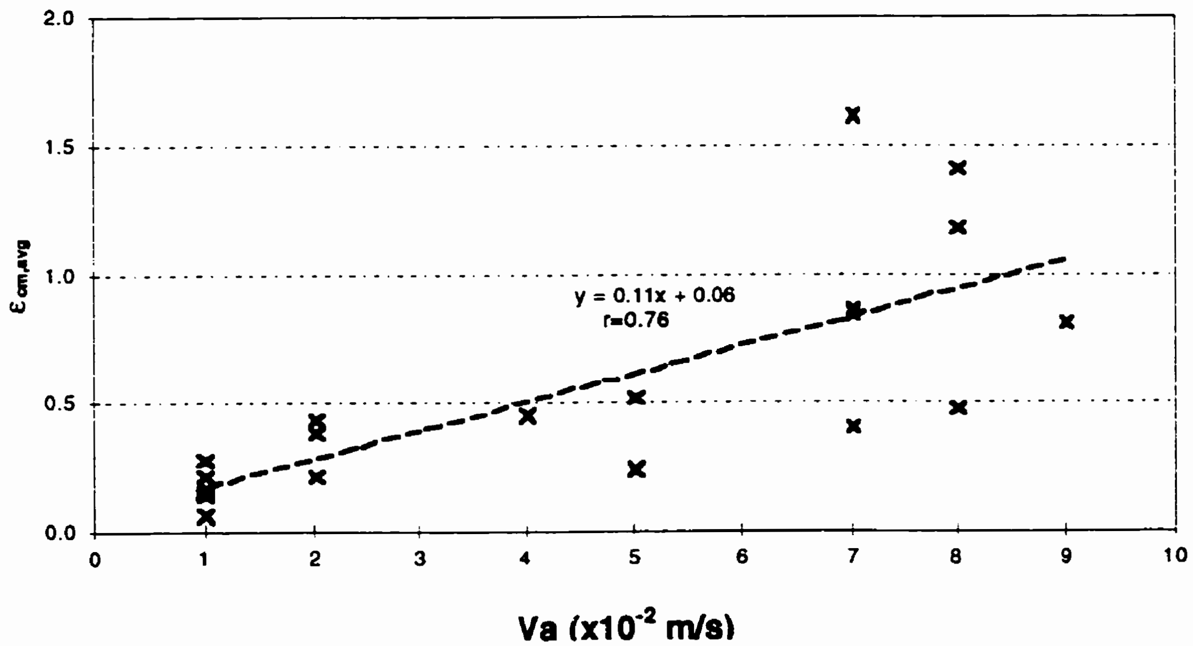
Table 4.3: Effectiveness and air velocity, all cases

		$\varepsilon_{cm,avg}$		V_a (X 10^{-2} m/s)	
Test	n	Maximum	Minimum	Maximum	Minimum
A	3	0.30	0.28	8	7
C	20	1.62	0.06	9	1
D	6	0.65	0.14	7	1
E	3	0.22	0.14	7	6
F	4	0.24	0.11	5	2
G	3	0.32	0.14	7	1

Figure 4.6 a) shows ε_{cm} as a function of V_a for all the cases. The ε_{cm} variations on the graph can be seen as two zones divided by Va below 0.07 m/s and Va above 0.07 m/s. For V_a below 0.07 m/s, effectiveness were found to be below 0.7 while for V_a above 0.07 m/s, $\varepsilon_{cm,avg}$ varied between 0.2 and 1.6. Figure 4.6 b) shows the change in ε_{cm} versus Va for case C only (one central diffuser). For values of Va between 0.01 m/s and 0.09 m/s, ε_{cm} has increased from less than 0.1 to more than 1.0. At Va equal to 0.01, ε_{cm} for case C is on the average equal to 0.17. The relationship between $\varepsilon_{cm,avg}$ versus Va can approximated using a regression line for test C. The relationship is similar to the relationship between ε_{cm} and q found in the previous section with r=0.76.



a) all tests



b) test C only

Figure 4.6: ε_{cm} versus Va

4.2.4. $\varepsilon_{cm,avg}$ and ΔTs

As introduced in the literature review, temperature differentials, ΔTs, between air supply Ts and room air temperature, Ta, create air movements in a room. High ΔTs (Ts<Ta) are expected to be better for an efficient ventilation. This is because the difference between cold and warm air masses creates a buoyancy effect. This effect is expected to increase the ventilation in the room and should also increase polluant removal effectiveness measured using ε_{cm}.

As shown in the previous section, ε_{cm} was strongly related to the flow of outdoor air, q, in the room (r>0.66). To isolate the effect of ΔT_s on values of ε_{cm}, experimental results were therefore categorized according to q values as listed in Table 4.4 and as shown in Figure 4.7.

In Table 4.4 a), results for test A (one central diffuser) showed that a variation in ΔTs from -5.8 to -8.2 °C corresponded to $\varepsilon_{cm,avg}$ variations smaller than 0.04. This result indicates that the effect of ΔTs on ε_{cm} was small for the room ventilated at q=19 L/s and for this type of diffuser layout.

In table 4.4 b), results for test C (on a central diffuser) showed that a variation in ΔTs from -4.6 to -5.4 °C corresponded to $\varepsilon_{cm,avg}$ variations of less than 0.16. These results indicate that the effect of ΔTs on ε_{cm} was small for the room ventilated at q close to 36 L/s and for this type of diffuser layout.

In Table 4.4 c), results for test C (one central diffuser) showed that a variation in ΔTs from -2.1 to -6.3 °C corresponded to an $\varepsilon_{cm,avg}$ variation of 0.72. As shown in Figure 4.7, the ε_{cm} augmented with ΔTs over a certain range (ΔTs=-2 to -5°C) and ceased to augment for ΔTs greater than -5°C. The coefficient of corellation, r, for the relationship between ε_{cm} and ΔTs was 0.36.

In this latter case, a linear assumption may however not be a correct model for the effect of ΔT_s on ε_{cm}. From the results, the pollutant removal effectiveness was improved with ΔTs but only up to a certain point (-5°C). At this point, the air coming out of the diffuser starts to fall straight down because of low supply, Ts, temperatures. The air does not mix significantly with the rest of the air in the room and there is less dilution as measured using ε_{cm}. Further data would however be required to determine the exact relationship between ε_{cm} and ΔTs.

Table 4.4: Effectiveness, ε_{cm}, and supply temperature difference ΔTs (q=constant)

a) Test A

ΔTs (°C)	$\varepsilon_{cm,avg}$	q L/s
-5.8	0.30	19
-6.0	0.30	19
-8.2	0.26	19

b) Test C

ΔTs (°C)	$\varepsilon_{cm,avg}$	q L/s
-4.6	1.41	36
-5.1	0.81	36
-5.4	1.62	33

c) Test C

ΔTs (°C)	$\varepsilon_{cm,avg}$	q L/s
-2.1	0.46	25
-2.9	0.52	27
-4.3	0.87	28
-5.1	1.18	27
-5.8	0.85	26
-6.3	0.48	25

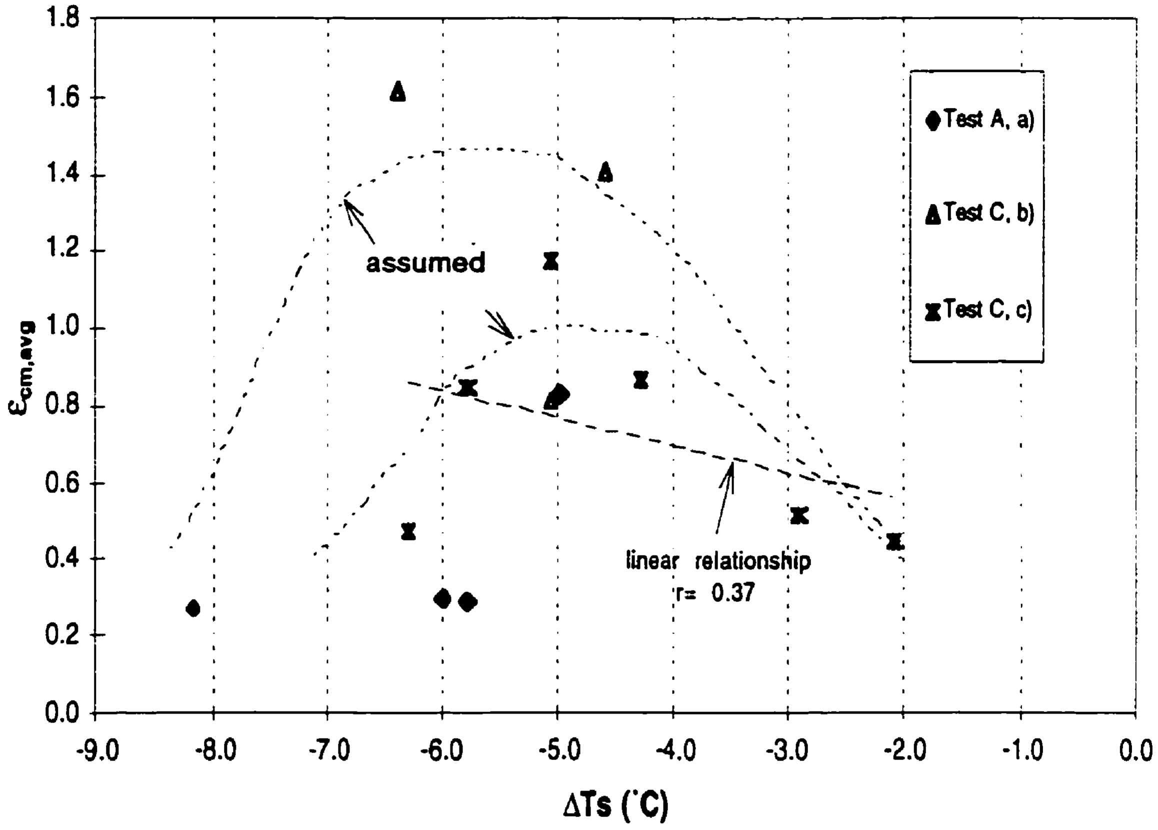


Figure 4.7: $\varepsilon_{cm,avg}$ versus ΔTs, selected cases, sorted by q (see Table 4.4)

4.2.5. ε_{cm} and n' measurements using SF_6

Results presented in the first section of this chapter included values of ε_{cm} for q equal to zero at the diffuser. In actual conditions, some portion of infiltration, n', was present in the room at q near zero. Under these conditions, the chamber was in negative pressure with respect to the adjoining rooms. Also, the air was leaving the room through the ceiling tiles because of the university's ventilation system.

The infiltration, n', in the room was measured using the SF_6 decay test as described in the methodology. With mixing fans in the room, results showed that zero diffuser flow values (test C) corresponded to an average n' of 0.39 air changes per hour in the room. This average was based on the average of four results with n'=0.39, 0.35, 0.37 and 0.48 air changes per hour in the room. The corresponding results observed for ε_{cm} (test C) varied between 0.1 and 0.4 for q=0 (see Figure 4.3, p.143). These results indicated that n' had an effect on the pollutant removal effectiveness, ε_{cm}, measured at low flow.

4.2.6. Effectiveness, ε_{cm}, and room uniformity, U

As described in the methodology, uniformity, U, represents the weighted average of the SF_6 concentrations at 5 points in the room. This index is similar to the air exchange efficiency index, ε_a described in the literature review. Results for ε_{cm} and U allow to observe whether local conditions (measured using ε_{cm}) are related to the global room conditions (measured using U).

Figure 4.8 presents $\varepsilon_{cm,avg}$ as a function of the calculated U in the room. For these tests, U varied between 4 and 26% with $\varepsilon_{cm,avg}$ varying between 0.06 and 0.52. For these cases, except for the highest values of uniformity, the $\varepsilon_{cm,avg}$ did not seem to be related to U as measured using the SF_6 concentrations.

Figure 4.9 shows two typical cases for which U was calculated. In figure 4.9.a) the diffuser flow is set to zero (infiltration only) and $\varepsilon_{cm,avg}$ is equal to 0.21. In Figure 4.9 b) the diffuser flow is set to 26 L/s and $\varepsilon_{cm,avg}$ is equal to 0.52. In figure a), concentrations were near 1.3 ppm while in b), concentrations were less with values around 0.10 ppm. In b), although U was greater than for a), concentrations at the different locations varied by less than 25 ppb.

These results show that $\varepsilon_{cm,avg}$ and U were not related for the experiments performed. This indicates that the local conditions of ventilation at a worksite were different from the conditions observed in the room.

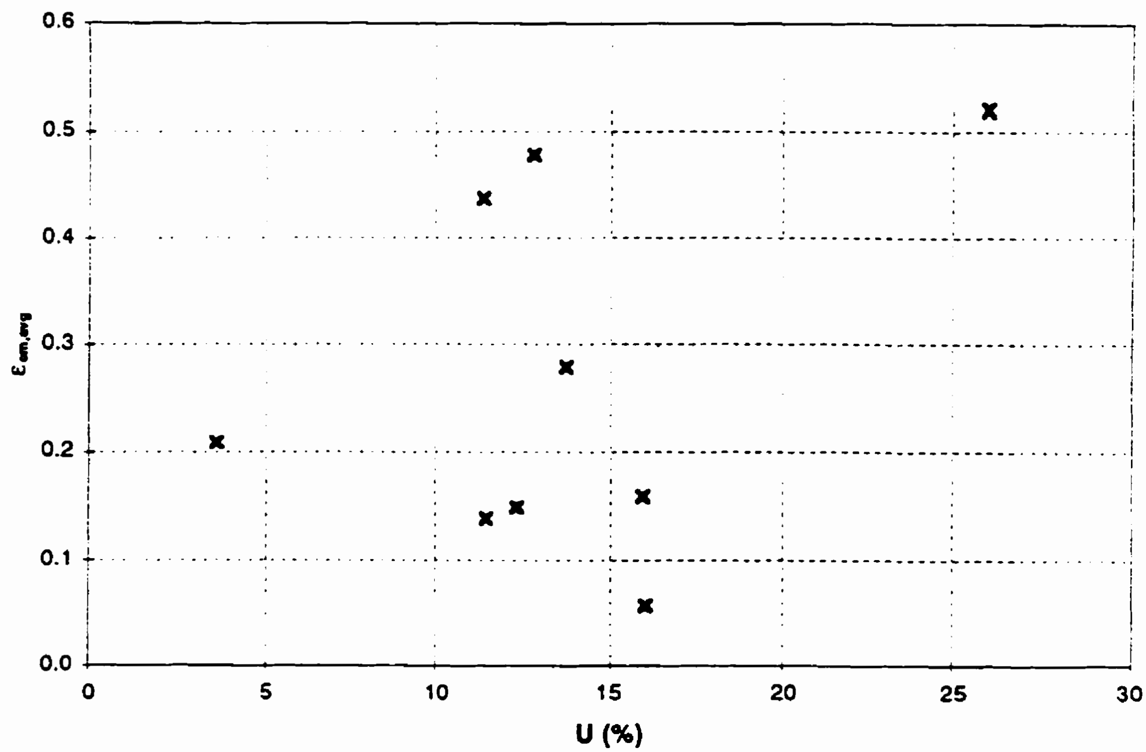
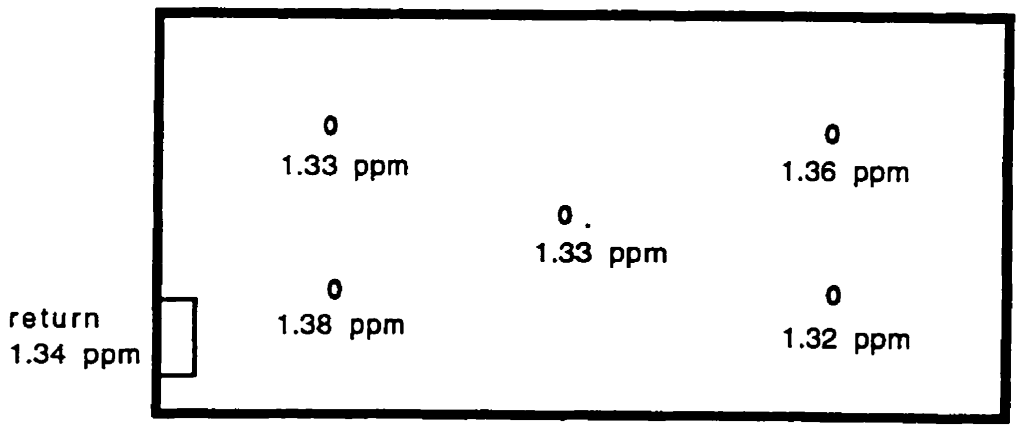
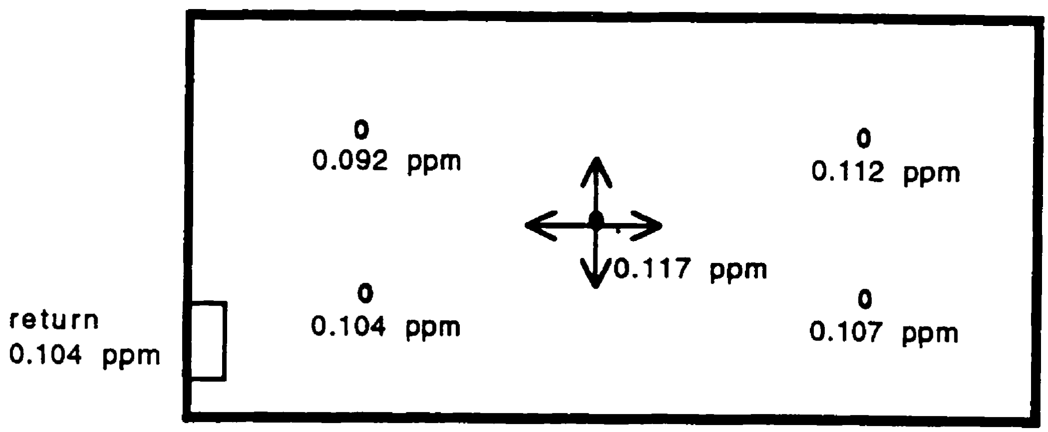


Figure 4.8: $\varepsilon_{cm,avg}$ as a function of uniformity, U



a) infiltration (q=0, U=4%, $\varepsilon_{cm,avg}$=0.21, Ta=24.8°C)



b) with diffuser flow (q=26 L/s, U=26%, $\varepsilon_{cm,avg}$=0.52, Ta=24.4°C)

Figure 4.9: U for two selected cases (case C)

4.2.7. Air velocities and diffuser flow rate

As described in the methodology, air velocities, Va, were measured in the test chamber for various flow, q, conditions. The results from these tests were expected to show a relationship between Va and q. This relationship was also expected to be similar to the relationship between q and ε_{cm}.

Table 4.5 lists the results of Va as a function of q for the cases studied in the test chamber. Va for all cases varied between 0.01 and 0.09 m/s. The corresponding values of q varied between 0 and 101 L/s.

Figure 4.10 a) shows the results obtained for Va as a function of q for all the tests performed. This figure represents the overall range of variation in the results. The dispersion of the points suggested a relationship with an increase of Va with respect to q. The relationship was however dependant on the number of diffusers used to deliver the air in the room.

Figure 4.10 b) shows the results for tests C, with air distributed from one central diffuser. An excellent linear relation was obtained for the relationship between Va and q with r=0.94 for test C. The slope of the line was 0.20 and passed at 0.009 m/s at the origin (q=0).

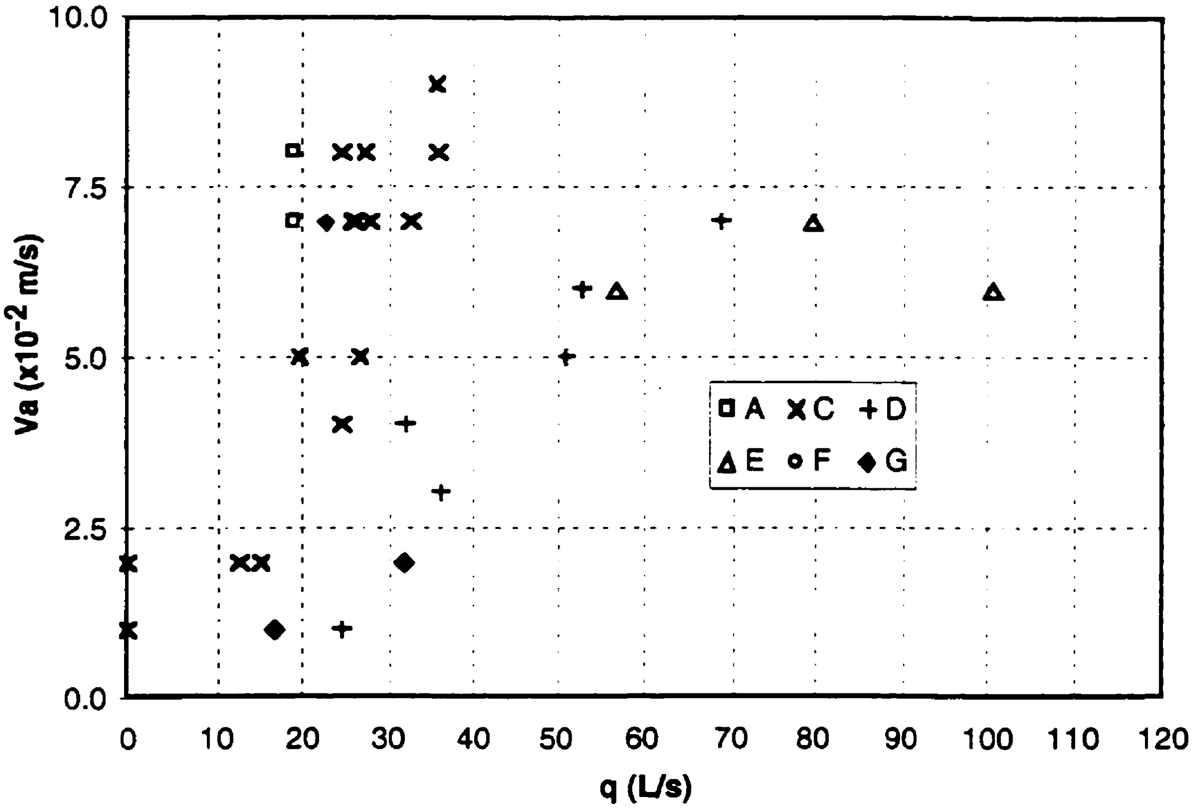
Figure 4.10 c) shows the results for tests D with air distributed by one central diffuser and one diffuser on the side. A very good regression line was also obtained for the relationship between Va and q with r=0.94. The slope of the line was 0.12 and passed below the origin (q=0).

These results indicated that Va in the room was strongly influenced by the air flow rate, q, in the room. The results also indicate that for the same flow rate, a higher number of diffusers (test D compared to test C) produced lower values of Va in the room.

The high correlation coefficient for Va versus q (r=0.94) was obtained using a linear relation. Therefore, the results indicated that Va could be linearly related to q. As shown earlier, an excellent linear relationship was also observed between pollutant removal measured using ε_{cm} and q (r>=0.76). Based on the similarity in the observed responses to q, the results indicate that ε_{cm} results can be used on a similar basis as Va and q measurements.

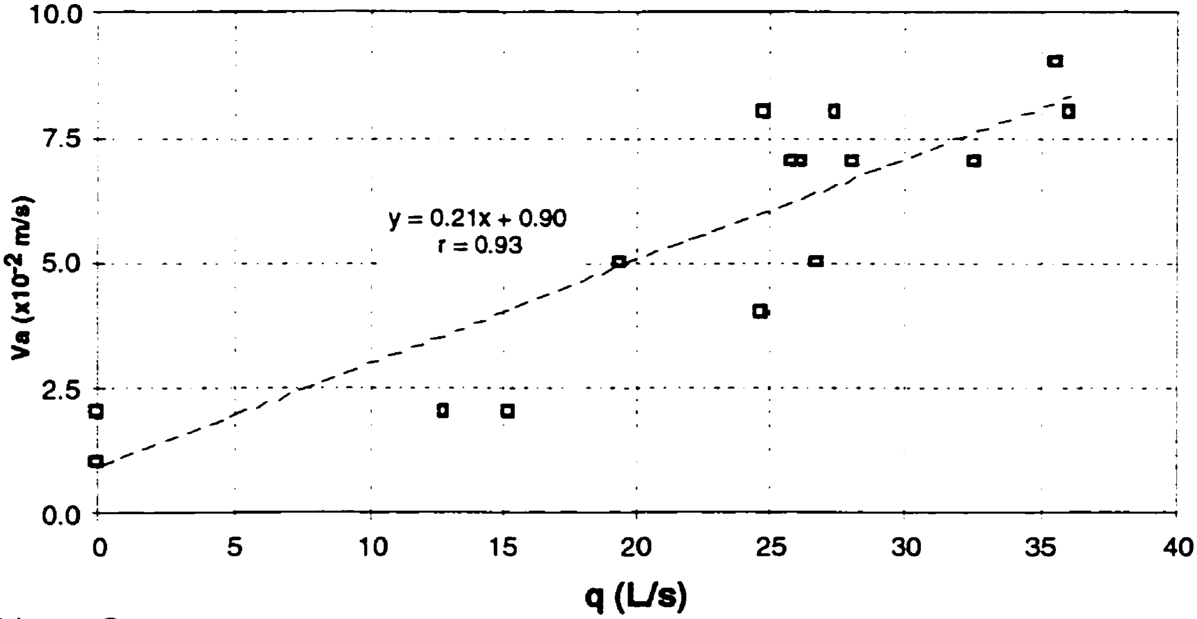
Table 4.5: Va and corresponding q (q=constant)

	Va ($x10^{-2}$ m/s)		q L/s	
n	Maximum	Minimum	Maximum	Minimum
3	8	7	19	19
20	9	1	36	0
6	7	1	69	25
3	7	6	101	57
4	5	2	80	29
3	7	1	32	17
39	9	1	101	0

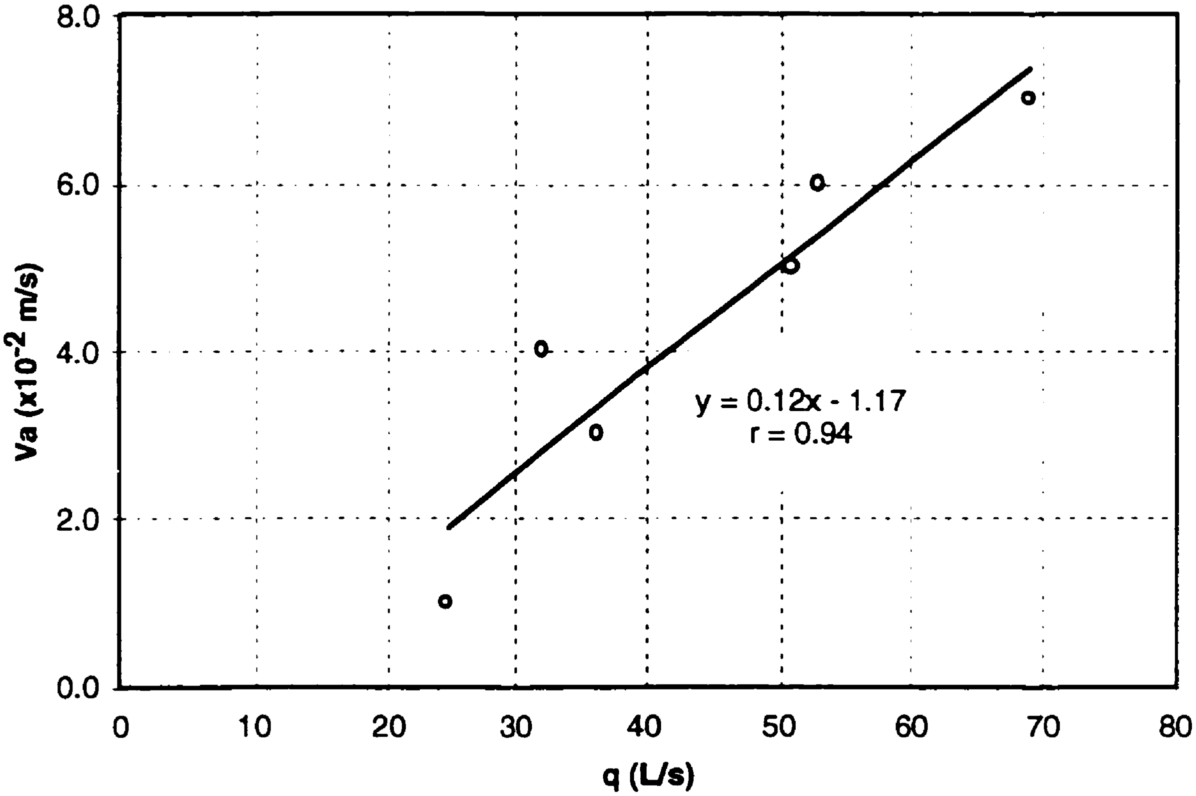


a) all tests

Figure 4.10: Va as a function of q



b) test C



c) test D

Figure 4.10: Va as a function of q

4.2.8. Room temperatures and rh versus Ts

This section presents the results of room temperatures, T_{room} (T_a or T_{air}, T_{wall}, T_{floor}), and relative humidity, rh, as a function of air supply temperature, T_s. As discussed in the literature review, these parameters were expected to be directly related to T_s. Also, a good relationship between T_s and these parameters was expected to be an indication that the conditions studied in the test chamber were thermally stable.

The results for T_{room} and rh as a function of Ts, are listed in Table 4.6 and are shown in Figure 4.11 and 4.12. Observation of the results in Table 4.6 and Figure 4.11 indicate that, as expected, the T_{room} were proportional to Ts. On the other hand, the results for rh, as a function of Ts as shown in Figure 4.12, were scattered over a wider range. The relationship between room temperatures and Ts was estimated using a linear relation. The coefficient of correlation, r, for Ta, T_{wall} and T_{floor} as a function of Ts were respectively 0.65, 0.75 and 0.81.

These results indicate that there was a very good relationship between room temperatures and Ts. Because room air temperatures, Ta, were directly related to Ts, the results also show that the room was well controlled thermally using the supply air from the ventilation system. The relationship between Ts and surface temperatures (T_{wall}, T_{floor}) was not expected to be as high as the relationship for Ta versus Ts. This result was expected because room surfaces had a much greater thermal inertia and were therefore expected to be less influenced by Ts then Ta.

Table 4.6: Variations in temperatures and rh compared to Ts

a) air temperature (°C)

	Ts	Ta
n	34	34
Maximum	23.0	28.4
Minimum	11.8	19.7
Average	19.4	23.9

b) wall temperature (°C)

	Ts	Twall
n	35	35
Maximum	23.0	26.8
Minimum	11.8	18.8
Average	19.3	22.8

c) floor temperature (°C)

	Ts	Tfloor
n	28	28
Maximum	21.5	26.7
Minimum	11.8	19.5
Average	18.6	22.8

d) relative humidity (%)

	Ts	Rh
n	22	22
Maximum	23.0	60
Minimum	16.5	18
Average	20.0	35

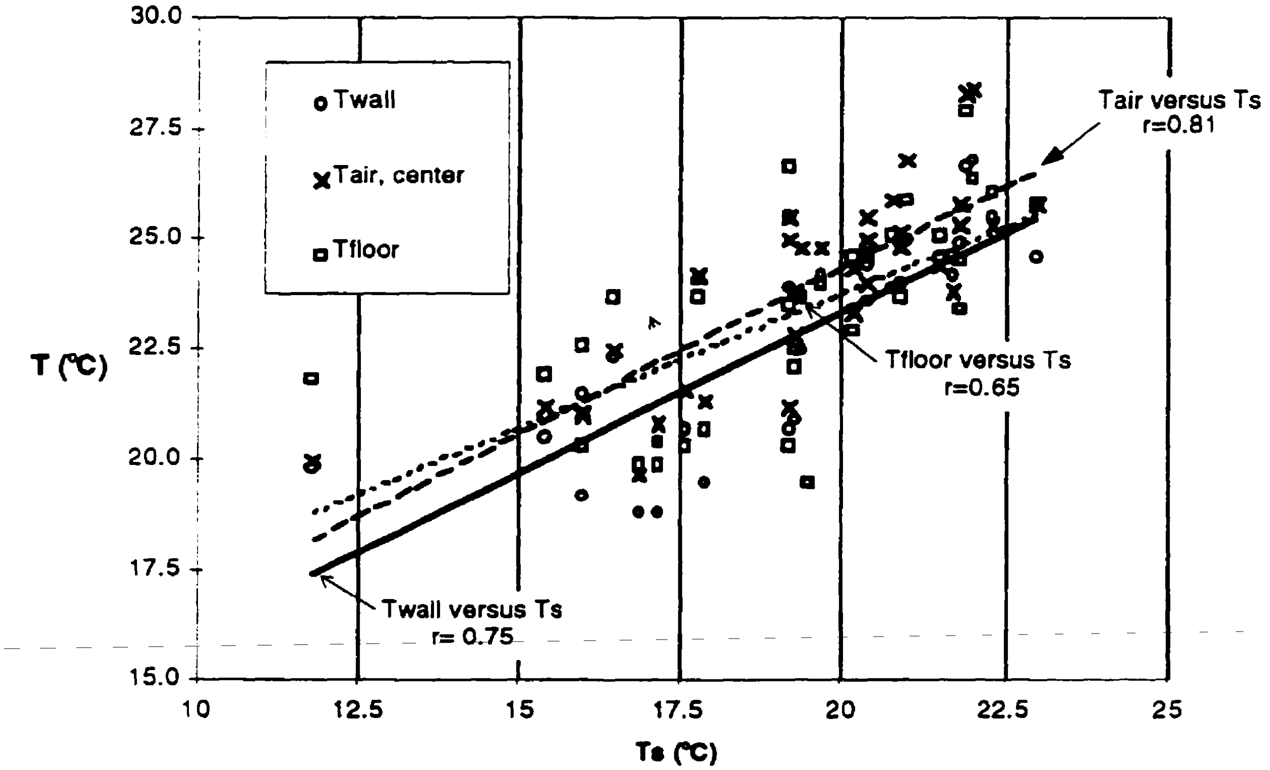


Figure 4.11: Room temperatures, (T_a, T_{wall}, T_{floor}) as a function of supply temperature, T_s

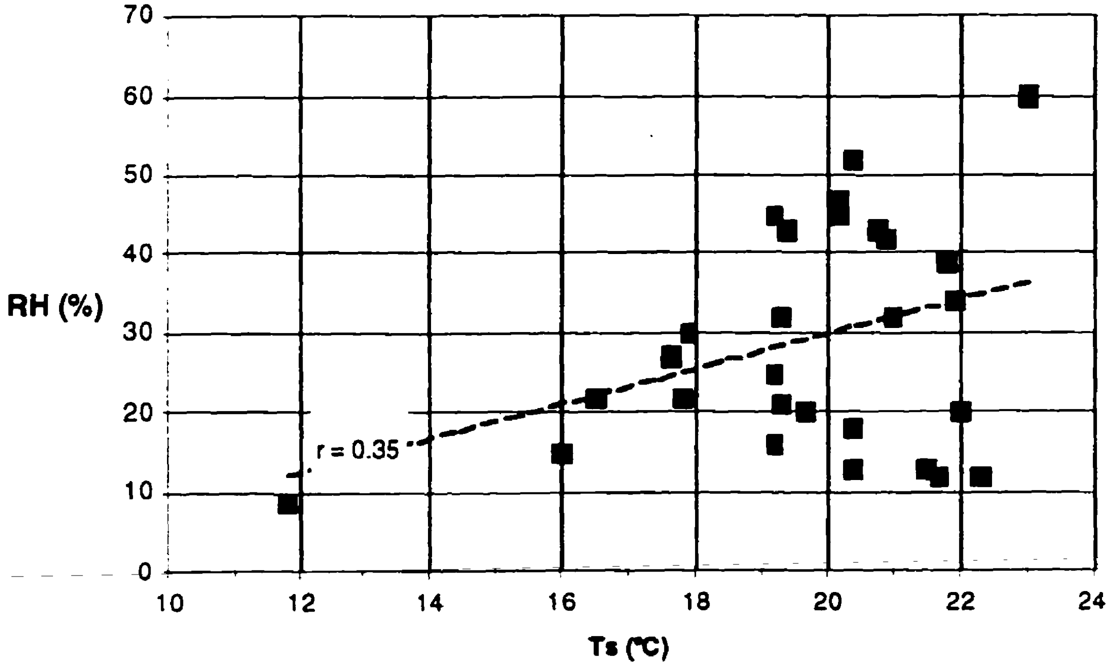


Figure 4.12: Relative humidity, rh, versus supply temperature, Ts

4.3. Field demonstration results

This section presents the results obtained following the demonstration of the ε_{cm} technique in actual conditions found in an office building. As described in the methodology, the field results obtained for ε_{cm} were expected to show the range of typical values of ε_{cm} for an interior and exterior office zone. Also, it was expected that there would be a relation between ε_{cm} and Va as measured at the worksites. Before these results are described, the conditions of occupancy observed during the tests are presented.

4.3.1. Occupancy

Measurements of ε_{cm} were made within working hours and during the night at the office building. The injection prototype (viii) was left unattended and performed ε_{cm} measurements automatically. The measurements in the centre zone and in the perimeter zone were taken while occupants were present around the injection device and on the floor of the office.

The centre zone results for ε_{cm} covered 17 hours beginning at the end of the working day (14:00) and ending the next day (9:00). This zone was occupied by one person between 15:00 and 17:00 on the first day and was also occupied by the same person between 7:00 and 9:00 on the next day. The offices next to the test site were occupied by four other people from 7:00 to 17:00. The ε_{cm}

measurements in this zone were made at a rate of three measurements per hour and 52 results of ε_{cm} were recorded (see CO_2 results Figure 4.13.a).

The perimeter zone results cover 6 hours of measurement beginning at 9:00 in the morning and ending at 15:00. The measurement zone was not occupied but the offices next to the test site were occupied from 7:00 to 17:00. The ε_{cm} measurements were also made three times every hour and 15 results of ε_{cm} were recorded for the perimeter office (see CO_2 results Figure 4.13.b).

4.3.2. Results

The results for the parameters measured on-site are listed in Table 4.7. These parameters included CO_2 concentrations, air velocity, Va and air temperatures, Ta. The pollutant removal effectiveness results were obtained using the CO_2 concentrations measured during CO_2 injections at the worksites and for the conditions presented in Table 4.7. These results are referred to as ε_{cm} results and were calculated using $\varepsilon_{cm,avg}$ as described in the methodology.

The diffuser flow to the zones, q_{diff} (constant air volume system) was maintained constant 24 hours a day (±5 L/s) for both zones tested. The outdoor air flow rate, q , was estimated to be 20% of the diffuser flow rate q_{diff}. This percentage was obtained from building personnel responsible for the operation of the ventilation system. The supply temperature, Ts at the diffusers was constant at 18 °C. The corresponding air temperature in the offices was constant (centre: 24 ±1 °C, perimeter: 23 ±1 °C) during the test period.

The CO_2 concentrations due to the presence of occupants (background concentrations) were measured in the centre of the office floor. These concentrations varied between 450 and 650 ppm. The variations in background concentrations of CO_2 are shown in Figure 4.13 and correspond to the concentrations measured in between CO_2 injection pulses. As shown in Figure 4.13 a) (centre zone), the background CO_2 concentrations reached a maximum (607 ppm) at 3:00 p.m. and decreased until 5:00 p.m. to 500 ppm. As shown in Figure 4.13 b) (perimeter zone), the background CO_2 concentrations varied by only 120 ppm and were therefore considered to be constant during the tests.

In comparison to the other parameters, Va results were different in the centre zone and in the perimeter zone. Va in the centre zone varied between 0.07 and 0.16 m/s or over a 0.09 m/s range. Va in the perimeter zone varied between 0.02 and 0.09 m/s or over a 0.07 m/s range. Va in the centre zone was on average higher (0.12 m/s) than Va in the perimeter zone (0.05 m/s).

Similar to Va results, the ε_{cm} results were different in the central and in the perimeter zones. For the workstation located in the centre zone, ε_{cm} varied over a 1.4 range (0.17 to 1.59) with an average of 0.48. For the workstation located in the perimeter zone, the value ε_{cm} varied over a 0.21 range (0.16 to 0.37) with an average of 0.25. The ε_{cm} measured in the centre zone was therefore 1.9 times the ε_{cm} measured in the perimeter zone. However, the ε_{cm} measured in the central zone varied more and reached a minimum (0.17) as low as the minimum observed for the perimeter zone (0.16).

As was the case for test chamber results, field results were organised to study the relationship between ε_{cm} and Va. The results for the two office zones are shown in Figure 4.14 and in Figure 4.15. Figure 4.14 shows Va and ε_{cm} as a function of time while Figure 4.15 shows ε_{cm} as a function of V_a.

Figure 4.14 shows the variations in ε_{cm} in time along with the variations in V_a measured at the test sites. Observation of the Figure 4.13 a) indicates that, for the centre zone, ε_{cm} and Va varied in a similar fashion over time. Similar results were obtained for the perimeter zone where the values of ε_{cm} followed changes in Va.

Figure 4.15 shows the results of ε_{cm} as a function of Va results for the perimeter and the central zone in the office building. The coefficient of linear correlation for the relation between ε_{cm} and V_a was calculated for each zone. The value of r was found to be r=0.67 for the perimeter zone and r=0.17 for the centre zone. In comparison r for the relation between ε_{cm} and V_a in the test chamber was equal to 0.76 for tests with one ceiling diffuser above the test site.

These results indicate that there was a stronger relation between ε_{cm} and Va for the perimeter zone than for the centre zone. However, although r for the centre zone is small, the slope of ε_{cm} as a function of V_a for the centre zone is the same as for the centre zone (see Figure 4.15). These results indicated that ε_{cm} results were related to Va results but that the strength of relationship (expressed using r) depended on the type of air distribution and room layout at a particular worksite.

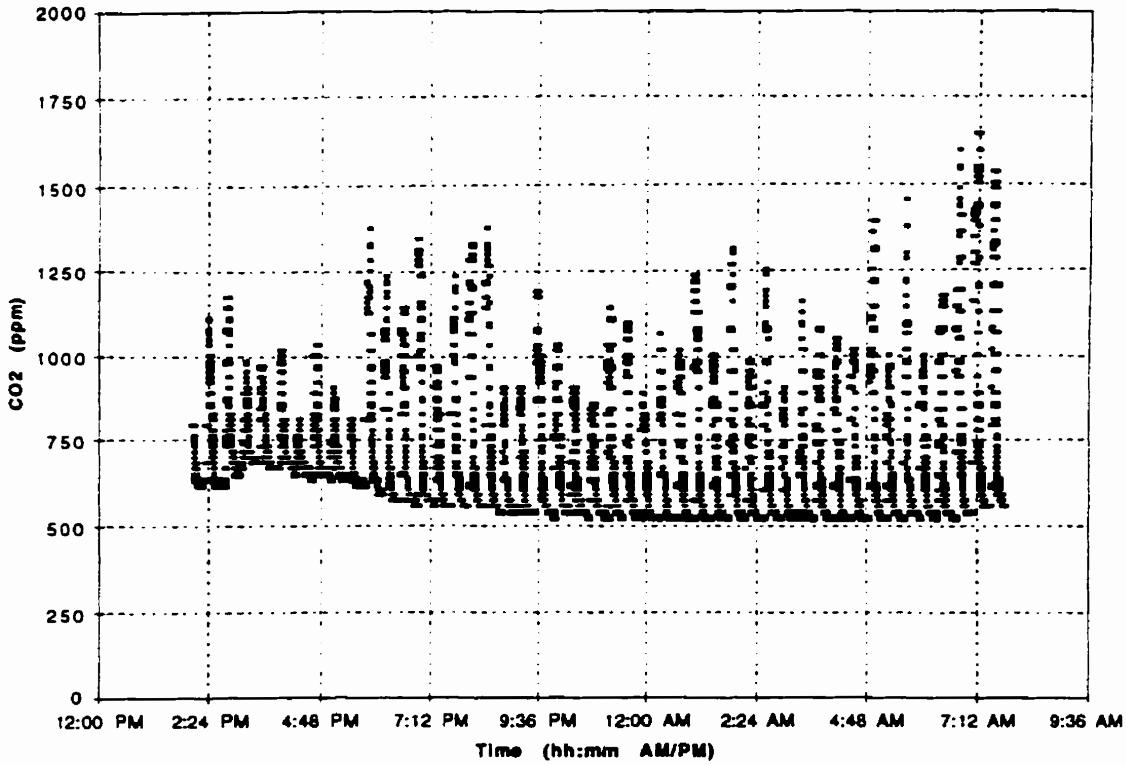
For a worksite such as the perimeter zone, there was a good relation between ε_{cm} and V_a. This was because the office space on the perimeter of the building was similar to a closed office with only one side opened to the rest of the floor. Air distribution through a single window diffuser at constant flow ensured a smooth and constant distribution of the air in the office space.

The office located in the centre of the building was mostly opened to the rest of the floor and air distribution was provided by diffusers located away from the worker's desk (see methodology). For this case, ε_{cm} and V_a were influenced by people's displacements around and inside the worksite as observed during the tests. This type of office layout and air distribution caused greater variations in ε_{cm} and in V_a than for the perimeter zone.

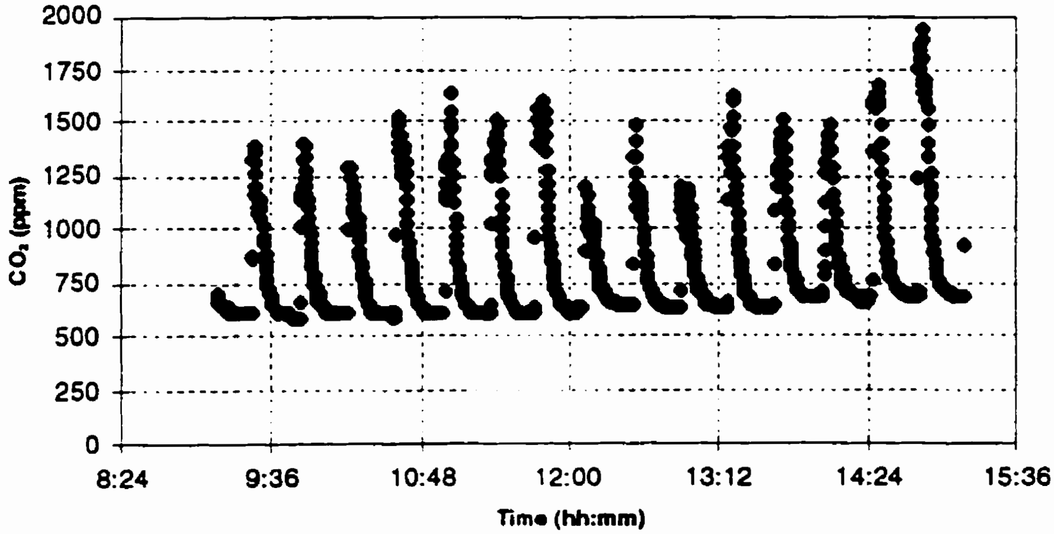
Further tests would be required to refine the observations made on the results obtained for the measurement of ε_{cm} in field conditions. Nevertheless, the results presented in this section showed that, based on the relationship between ε_{cm} and V_a, the method was able to produce field results that were consistent with the results obtained in the test chamber. Results also indicated that ε_{cm} was influenced by office layouts and the location of the diffusers in the office space.

Table 4.7: Summary of field results

Parameter		Centre	Perimeter
total airflow estimated from diffusers, q_{diff} (L/s)	constant	160	90
q (outdoor air) estimated using 20% outdoor air (L/s)	constant	30	20
CO_2 (ppm)	n	118	37
office centre ($C_{m,o}$)	maximum	607	627
	minimum	450	509
	average	500	572
CO_2 (ppm)	n	4453	1355
worker/injections ($C_{m,o}$ & C_m)	maximum	1646	1945
	minimum	528	591
	average	684	822
Air velocity (x10^{-3} m/s)	n	45	60
worker (Va)	maximum	16	9
	minimum	7	2
	average	12	5
Air temperature (°C)	n	45	60
worker (Ta)	maximum	24	24
	minimum	24	23
	average	24	23
Supply temperature, (°C) diffuser (Ts)	average	18	18
Effectiveness	n	52	15
worker ($\varepsilon_{cm,avg}$)	maximum	1.59	0.37
	minimum	0.17	0.16
	average	0.48	0.25

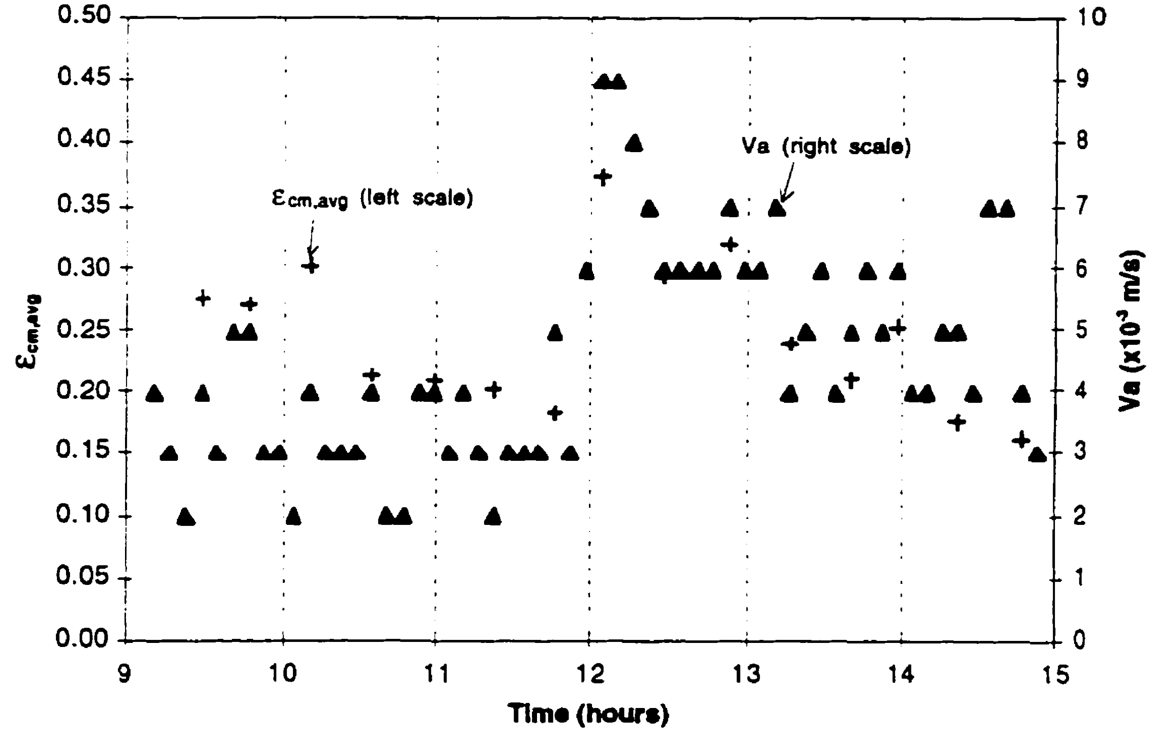


a) centre zone

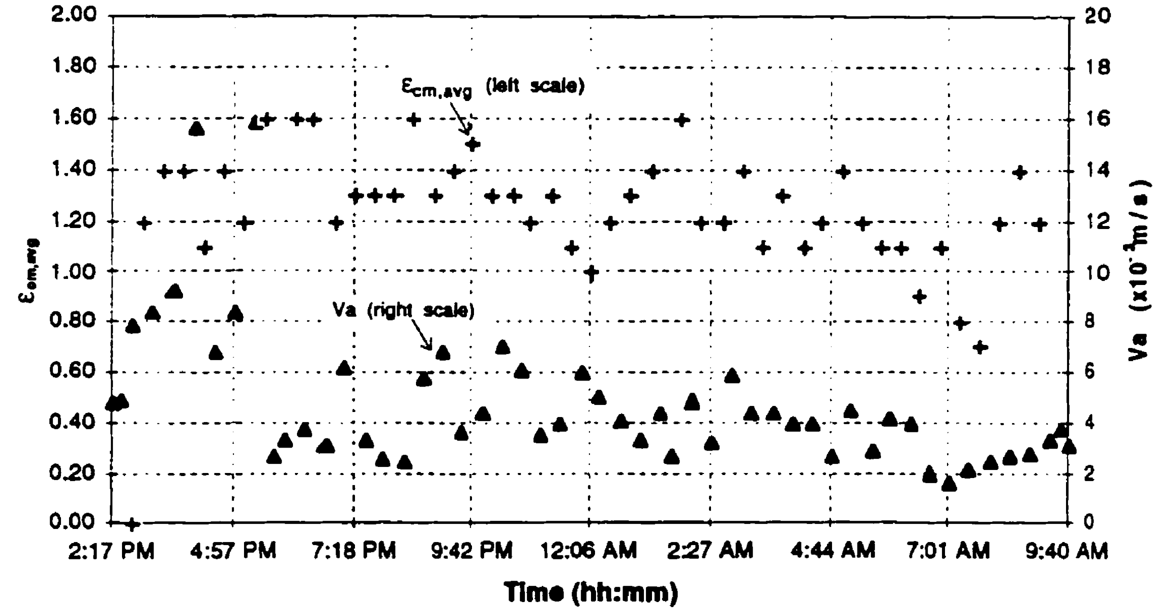


b) perimeter zone

Figure 4.13: CO_2 concentrations measured at the test sites



a) centre zone



b) perimeter zone

Figure 4.14: Test results for ε_{cm} and V_a measured in time at the two worksites

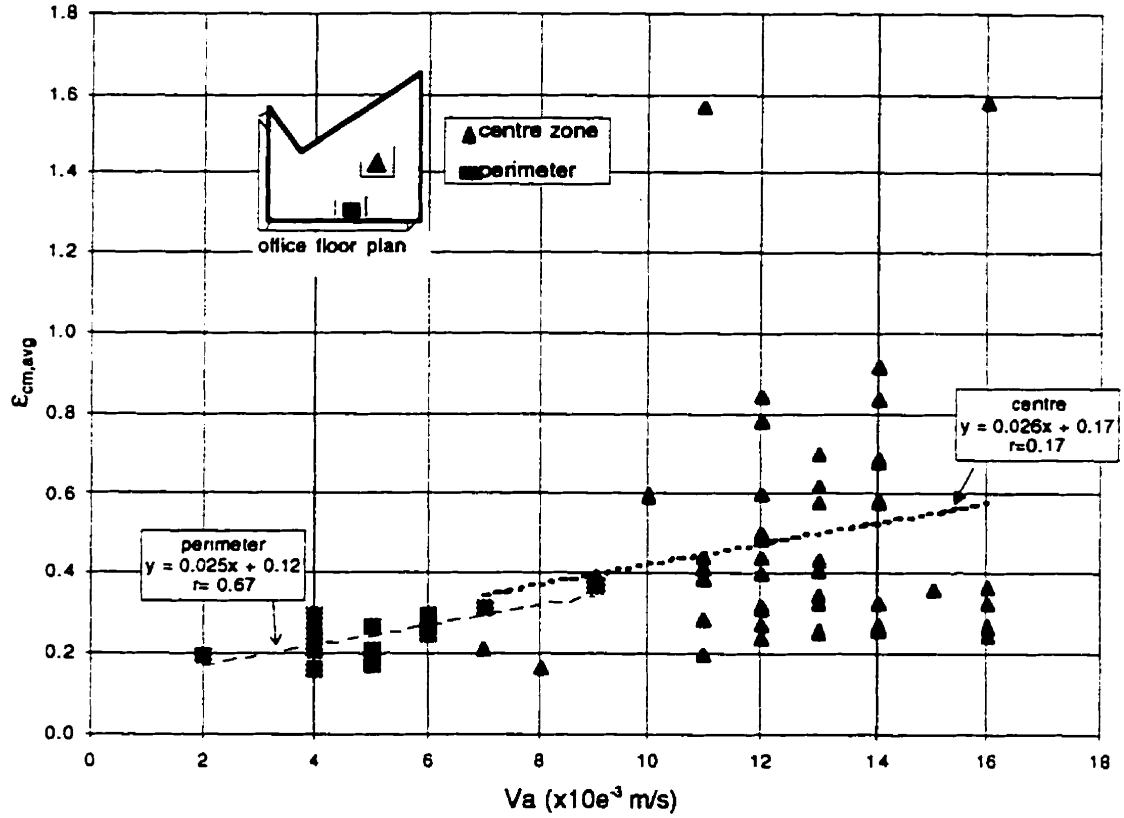


Figure 4.15: Results for ε_{cm} versus V_a for centre and perimeter zones tested in the office building

5. DISCUSSION

As stated in the introduction, the main objective of this investigation was to develop and test a new method, ε_{cm}, for the evaluation of pollutant removal effectiveness in office buildings. Test results presented in the previous chapter indicated how the ε_{cm} method developed [154, 155, 156] responded to the most important parameters expected to affect VE in office buildings (q, V_a, ΔT_s, T_a, T_{room}, U). The following discussion combines these results in order to obtain a perspective on the effect of room conditions on VE in office buildings.

The discussion covers the main aspects related to the measurement of ε_{cm} in office buildings. First, results are discussed in terms of the effect of room conditions on ε_{cm}. Next, experimental results are discussed in terms of the models that can be developed to predict ε_{cm} as a function of air flow rates. Third, the ε_{cm} results are discussed using the results obtained from other research studies described in the literature review. Next, the various sources of error associated with the method are discussed and, finally, the application of the method for design and evaluation of ventilation for IAQ are discussed.

5.1. Effect of room conditions on ε_{cm}

As described in the literature review, pollutant removal effectiveness measured using ε_{cm} evaluates the ability of a ventilation system to remove pollutants from a space. In this investigation, the ε_{cm} method was applied and produced several results concerning the relationship between ε_{cm} and various room conditions.

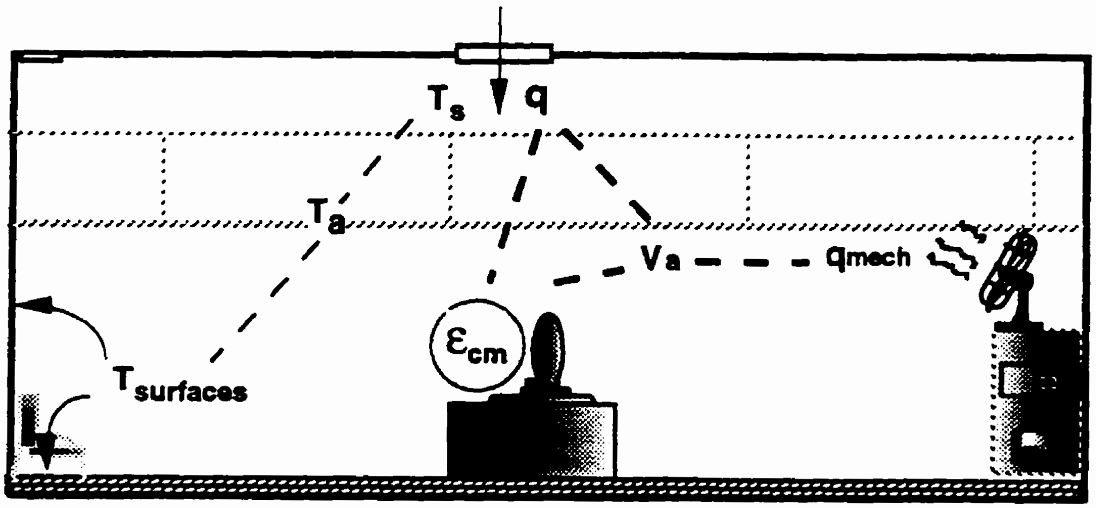
As it was the case for previous studies described in the literature review, room conditions were varied within a certain range and the response of the method was observed under these conditions. For each set of condition, ε_{cm} and room condition data were compared to one another and a set of relationships was obtained. These relationships were summarised in a series of diagrams shown in Figure 5.1 to Figure 5.4.

The first figure, Figure 5.1, shows the assumed and the observed relationship for ε_{cm}. At the beginning of the tests, it was expected that ε_{cm} would be an equal function of all the room parameters. In other words, each parameter was assumed to have the same impact on pollutant removal effectiveness. Experimental results, however, allowed a more precise evaluation of the ventilation process that occurred in the room.

This process can be expressed by a series of functions that are related as shown in Figure 5.2. These functions, designated by f's, represent a particular relationship between ε_{cm} and a parameter measured in the test chamber or in the field.

For the test chamber, functions f1 to f5 represent the relation between ε_{cm} and q. Function f8 relates ε_{cm} to V_a and functions f6 and f7 relate Va to q. Function f9 represents the relation between ε_{cm} and temperature differences, ΔTs. Functions f10 to f12 represent the relationship between Ts and room temperatures (T_{room}:T_a, T_{wall}, T_{floor}). For the field study, function f13 and f14 represent the relation between ε_{cm} and V_a.

Figure 5.3 shows the relations observed between ε_{cm} and q for the test chamber and the field demonstration. Functions f1 and f2 are the functions observed for constant q cases and one diffuser. Function f3 represents the average of all the tests conducted in the test chamber (all q, all diffuser types). Functions f4 and f5 represent the relation between ε_{cm} and q. The field results are also shown along with the ASHRAE standard [49] recommendation for minimum outdoor air requirements.



assumed: $\varepsilon_{cm} \approx F(q, Va, q_{mech}, Ts, Ta, \Delta Ts, T_{surfaces}, U, n')$

observed: $\varepsilon_{cm} \approx f(q, Va) + \phi\,(q_{mech}, Ts, Ta, \Delta Ts, T_{surfaces}, U, n')$

Figure 5.1: Assumed and observed effect of room conditions on ε_{cm}

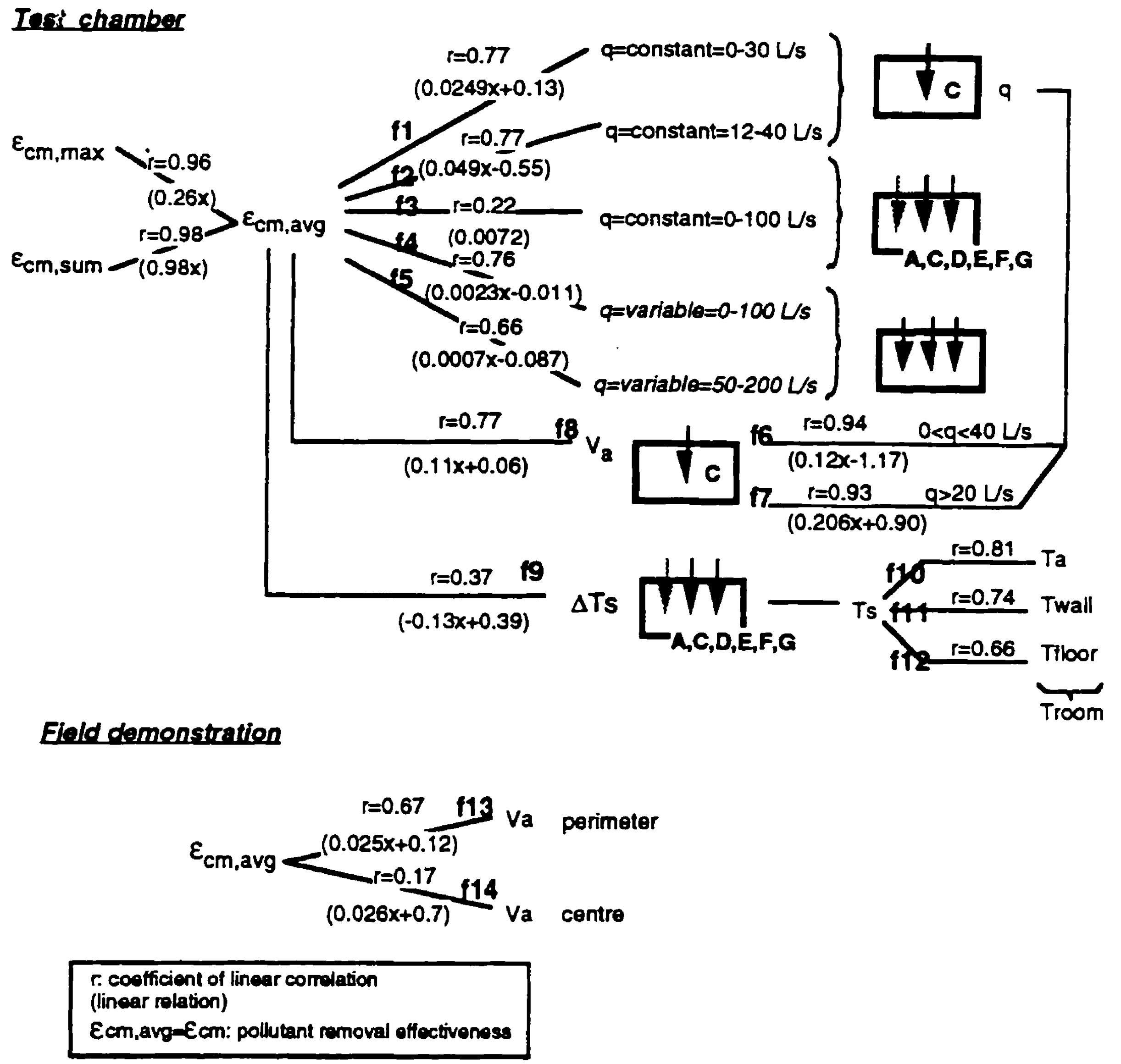


Figure 5.2: Relationships obtained from the test chamber and field demonstration experiments

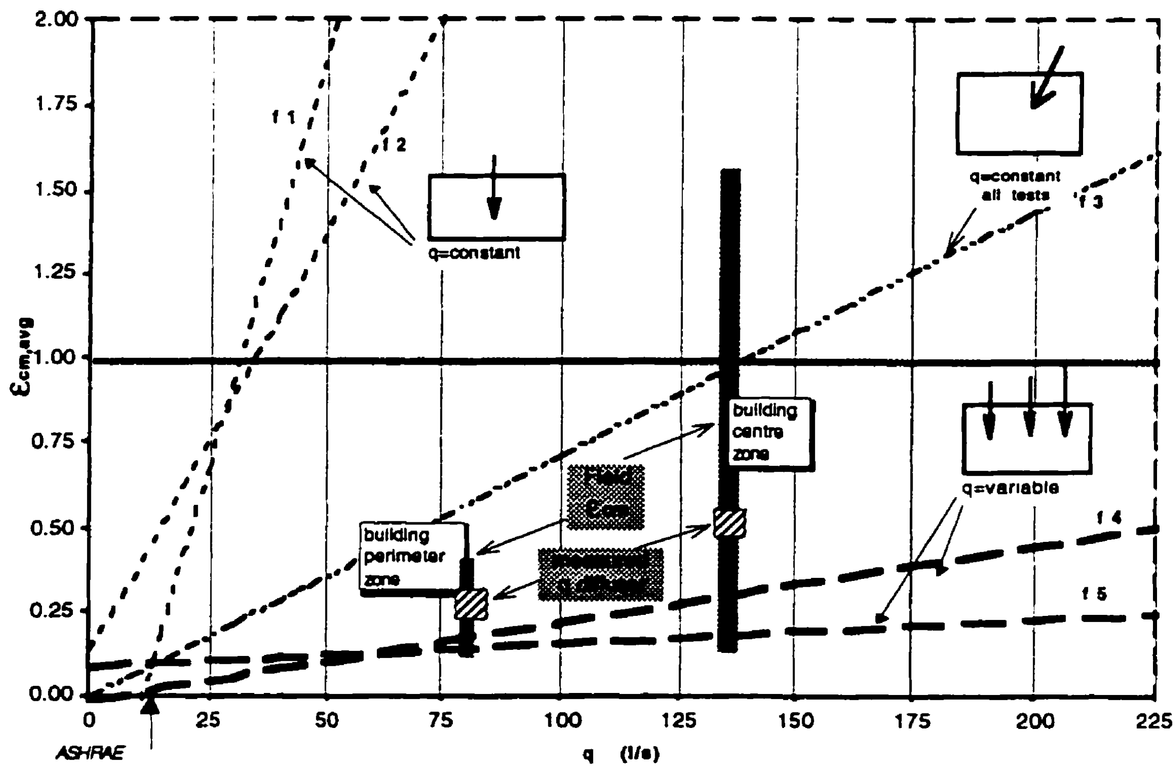


Figure 5.3: Comparison of the relationships observed between ε_{cm} and q

At first glance, the process of pollutant removal in the room appears to be a complex combination of several factors. However, results in the chamber clearly indicated that two parameters were found to significantly affect ε_{cm}. These parameters were the amount of air, q, delivered at the diffuser (f1,f2,f3,f4,f5) and the air velocity, V_a, in the room (f8, f13, f14).

Early results [155] clearly indicated the positive effect of using a fan on the mixing conditions in the room. The ventilation provided by fans (q_{mech}) was therefore an important factor in increasing pollutant removal efficiency. The presence of these fans was observed during the field demonstration tests and can therefore not be neglected as important sources of ventilation in actual office buildings.

The study of temperature results clearly indicated that the room temperatures were directly related to air supply temperatures (f10:r=0.81; f11:r=0.74, f12:r=0.66). The ε_{cm} was not related to air supply temperature difference (ΔTs) as estimated using a linear relationship (f9:r=0.37). However, a different relationship (see results) may explain these observations better. Most likely, the thermal conditions in the room operate differently under different temperature ranges and this causes the ε_{cm} to vary depending on the temperature range.

The most important parameter affecting pollutant removal effectiveness, ε_{cm} was the amount of outdoor air delivered into the room, q. Figure 5.3 permits to observe the relationship between this parameter and ε_{cm}. The q values observed in the room can be classified in three types.

Function f1 and f2 represent the case of a single diffuser located above a person. This type of condition is similar to the case assumed for the two-compartment model. The air is well mixed and delivered at a flow rate sufficient to maintain a high ε_{cm} with relatively small flow rates. In this case, effectiveness is obtained with only a small usage of the capacity of the diffuser.

Function f3 is a function that was obtained using all the test results described in the previous chapter. This function represents an "average" ε_{cm} as a function of q for all the experimental results obtained in the test chamber. It may also be seen as a random sample taken out of a field study that comprised the same conditions as those tested in the chamber.

Functions f4 and f5 represent the relation between ε_{cm} and q observed for the variable air volume, VAV, tests. Contrary to constant q functions (f1 and f2) transient q tests do not represent ideal conditions. Instead, these conditions were closer to the conditions observed in the field.

5.2. Model predictions

Two types of models were used to describe the relationship between ε_{cm} and the amount of outdoor flow rate, q, distributed in a room. First, the two-compartment model was used as described in the literature review and in the methodology. As it will be recalled, the two-compartment model was a physical model based on the description of a room using two compartments.

Another type of model tested was an empirical model based on the ε_{cm} results. The empirical model relates ε_{cm} to q but does not necessitate any assumptions concerning the behaviour of air movements inside of a room. Empirical models use linear regressions and are applied to calibrate or adjust results to observed conditions. Contrary to the two-compartment model, linear regression models combine the effect of all the room parameters into a single relationship.

5.2.1. Comparison with two-compartment model

Figure 5.4 shows the ε_{cm} results as a function of q for the results obtained in the test chamber and the ε_{cm} response to q as predicted using the two-compartment model described earlier (methodology, literature review). The two-compartment model predictions are shown using three solid lines. Each line corresponds to the equivalent flow rate, q', that would be observed at the centre of the room if ε_{cm} were set constant at 0.5, 1.0 and 1.5. The experimental values of ε_{cm} are the values obtained for test C in the test chamber (one diffuser case). This case was selected because the conditions corresponded the most to the assumptions of perfect mixing implied in the model.

As can be seen, experimental results of ε_{cm} fall within the values predicted using the two-compartment model over the range of q from 10 to 35 L/s. The two-compartment model is however not appropriate for predicting the ε_{cm} values for q close to zero and for q>35 L/s. The measured values of ε_{cm} for q=0 were mostly influenced by the infiltration in the chamber (n'). Infiltration, as calculated using SF_6 tests, could be as high as 9 L/s when q=0. Infiltration was however expected to decrease significantly as q increased and the room was pressurised with respect to the adjoining zones. If infiltration is included in the predictions, the ε_c for q=zero would intercept the x-axis at 0.2 instead of passing through the origin.

The values of ε_{cm} for q>35 L/s do not correspond to predicted ε_c values because the room conditions at higher flow rates are less uniform and the conditions are not conform to the assumptions of the model (steady-state, full room mixing). These differences were also observed in the test chambers where the relationship between ε_{cm} and q was found to vary according to the range of q.

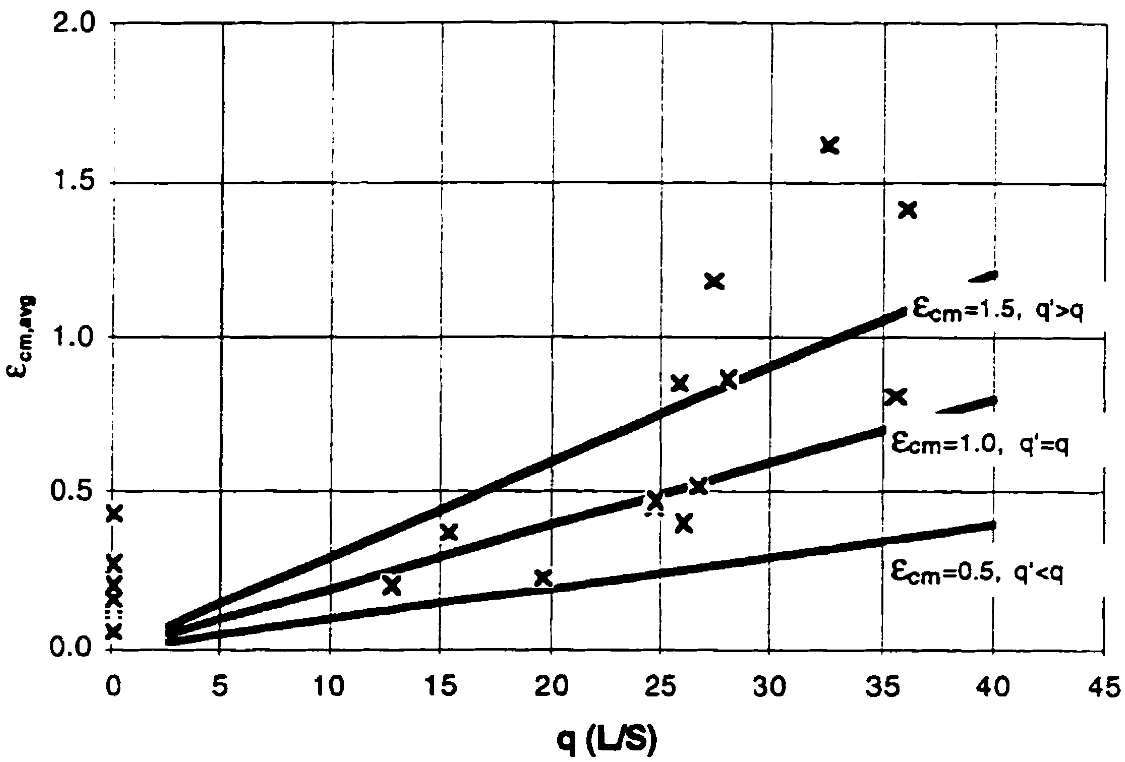


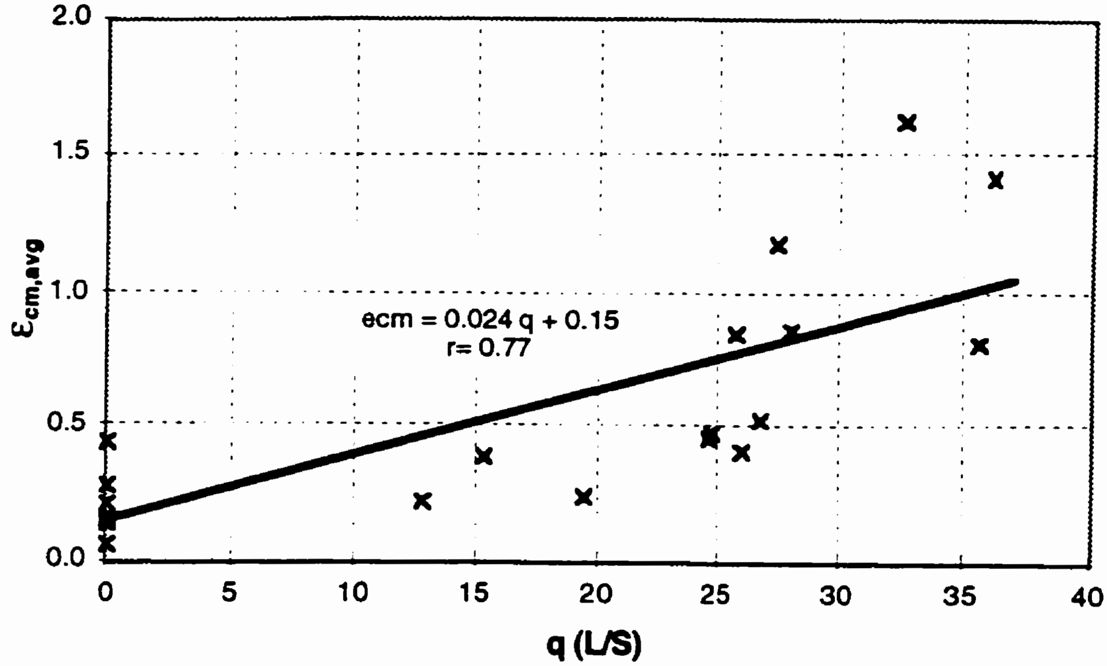
Figure 5.4: Experimental results compared to two-compartment model (test C)
(Solid lines indicate the predicted results based on the two-compartment model for an effective flow rate, q', obtained for ε_{cm}=0.5, 1.0 and 1.5)

5.2.2. Regression analysis of ε_{cm} versus q

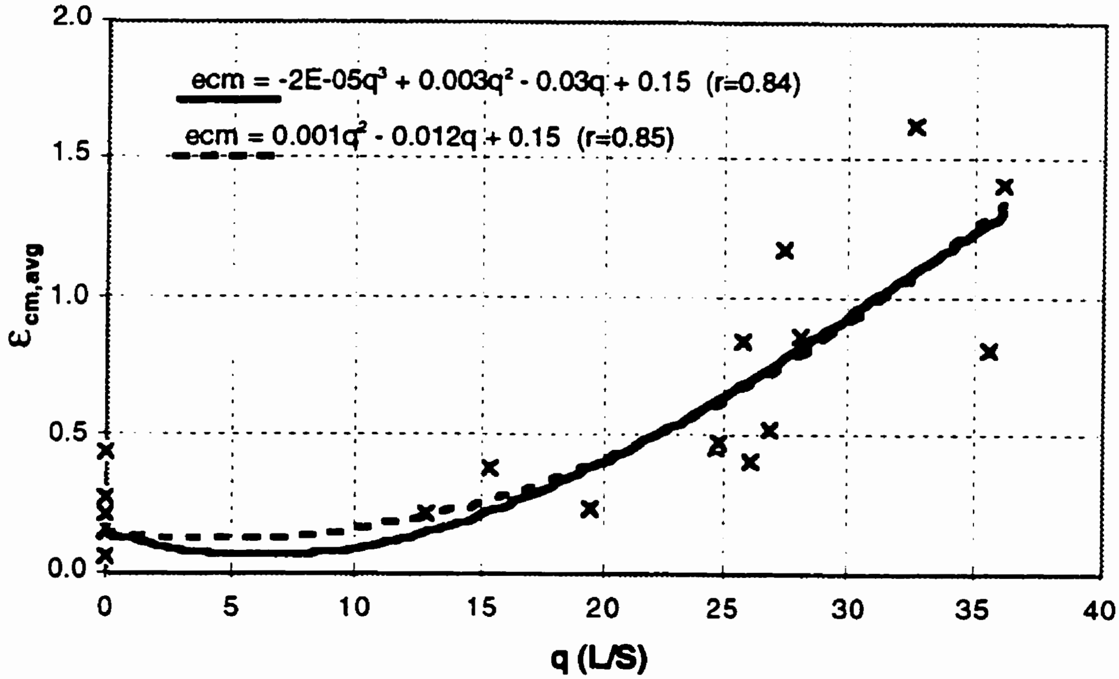
Regression analysis was used over the results to obtain a set of linear relationships to express the relation between ε_{cm} and q. Even though the coefficients of linear correlation observed were high ($0.66<r<0.77$) and graphs of the data suggested a linear relation, other types of relations may be better fitted to describe the process of ventilation studied.

Figure 5.5 shows three relations that were used to express the data obtained for ε_{cm} versus q (test C). In Figure 5.5 a) a straight line relation was used for ε_{cm} versus q ($\varepsilon_{cm}=m\text{q}+b$). In Figure 5.5 b), second and third order polynomial functions were used ($\varepsilon_{cm,avg}=b+m_1q+m_2q^2$ and $\varepsilon_{cm,avg}=b+m_1q+m_2q^2+m_3q^3$). In Figure 5.5 c), an exponential function was used ($\varepsilon_{cm,avg}=K_o+K_1e^{(q-k2)}$) and lines were obtained with the K parameters (K_o:zero ε_{cm}, K_1:scale, K_2:asymptote).

Based on the coefficients of correlation, r, obtained for each of the three types of regression analysis, the polynomial expressions provided the best approximation of the relation between ε_{cm} and q ($r=0.84$ and $r=0.85$) . Even though the shape of the exponential curves seemed to match the data for lower q range ($q<30$ L/s), the r value obtained was less than 0.50. The linear relationship between ε_{cm} and q provided an estimate in between the other two types of relationships with $r=0.77$.

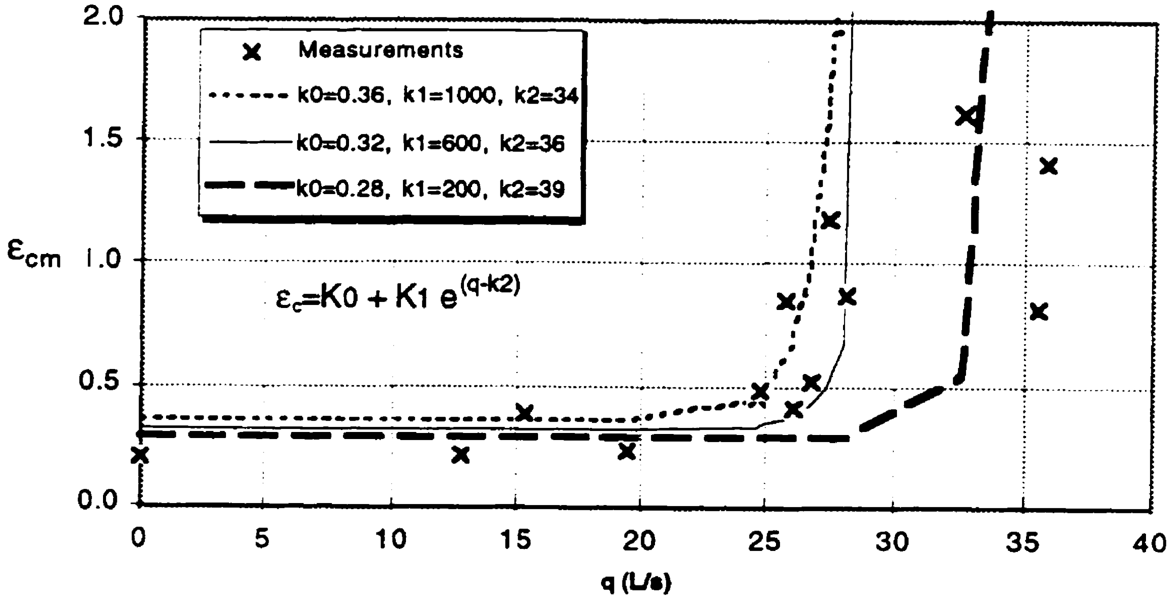


a) Linear model



b) Polynomial

Figure 5.5: Regression analysis results for ε_{cm} as a function of q



c) Exponential

Figure 5.5: Regression analysis results for ε_{cm} as a function of q

5.3. Range of ε_{cm} results

The range of ε_{cm} observed in the chamber and in the field can be compared with the ranges of air exchange efficiency, ε_a, and pollutant removal effectiveness, ε_c reported in the literature review. These ranges are shown in Figure 5.6. For each study, the ranges reported were obtained by selecting the lowest and the maximum VE values reported. The values of ε_c were converted on a percentage scale (multiplied by 100) to compare these values on the same scale as the ε_a values.

For all the experiments the ε_{cm} results varied over a range of values similar to the other ε_c studies. The ε_{cm} range for the tests conducted in the experimental chamber (6 to 160%) and in the field (16 to 160%) were similar to the ranges observed by Skaret and Mathisen (20 to 140%) [57] and this range was also close to the range observed by Fisk (63 to 130%) [103].

If ε_a is assumed to be equal to ε_c (ε_a=1ε_c) the lower ε_{cm} ranges observed in the current study are comparable to the ranges observed by Sandberg (20 to 40%) [97] where the worst case ventilation conditions were simulated in a test chamber. The maximum values of 160% for ε_{cm} falls in between the maximum ε_a values observed in the other studies (140 to 240%).

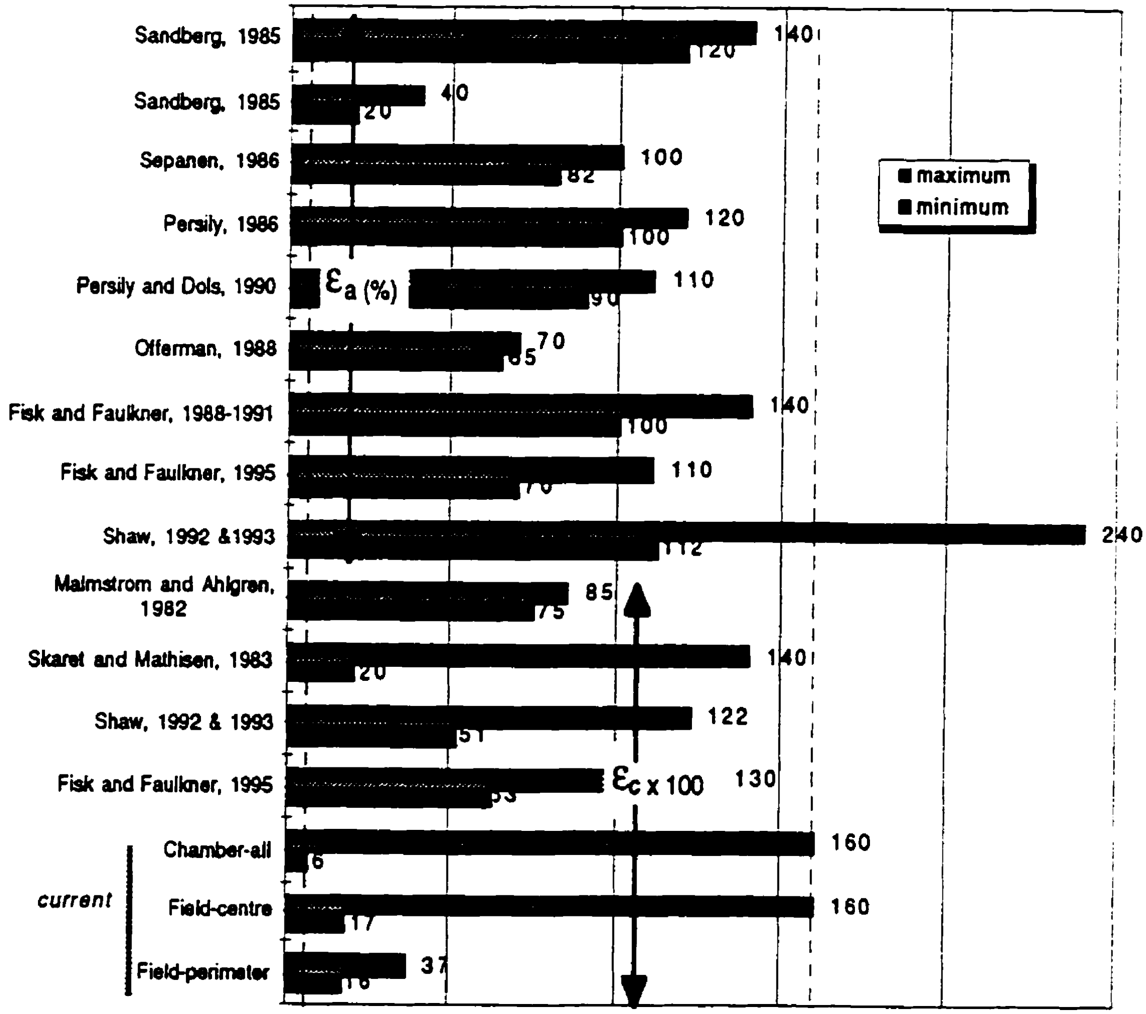


Figure 5.6: Comparison of observed ε_{cm} ranges results with ε_a and ε_c ranges observed in other VE studies

5.4. Sources of error

Sources of error associated with the measurement of ε_{cm} can be divided in two classes: errors caused by the calibration or the use of the CO_2 injection device (systematic error) and the errors due to the fluctuations of the measured ε_{cm} (random errors).

In practice it was observed that systematic errors due to the CO_2 monitor were minimal. If the monitor was verified and calibrated at regular intervals, the changes in calibration over time or drift of the instrument were not found to be important (less than 50 ppm per week). Because the device was automated, there was no error associated with the operator of the injection device.

Random errors associated with ε_{cm} results were estimated in two ways. First, the random error specified by the manufacturer of the CO_2 detector (100 ppm) was introduced into the formula used for ε_{cm} calculations to obtain an estimated difference between measured and actual ε_{cm} [88]. Second, the coefficient of variance of the method, CV, was calculated for test chamber results.

The error due to the CO_2 monitor was calculated by introducing $C_m=1500 \pm 100$ ppm and $C_{mo}=500 \pm 100$ ppm in the formula of $\varepsilon_{cm}=100/(C_m-C_{mo})$. For these CO_2 concentrations, ε_{cm} varies between 0.08 and 0.125 or $\varepsilon_{cm}=0.10 \pm 0.03$.

The random error associated with the ε_{cm} method was also estimated using the coefficient of variance for the results obtained in the chamber. The coefficient of variance, CV, is the ratio of standard deviation of a series of measurements (of the same quantity) expressed as a percentage of the mean of the measurements. For three case of constant air flow (q=19 L/s, Va=0.12 to 0.20 m/s, Ta=19.1 to 20.7°C, Ts=10.3 to 14.8°C, ΔTs=6.3°C), the CV for the ε_{cm} method was between 17 and 26%. For the same conditions but with mixing fans operating in the room, the CV was between 20 and 35% [155]. These values indicate mainly how stable the conditions were in the room during a test and are consistent with variations observed in the test results.

5.5. Application of the method

The ε_{cm} measurement system, in its present form, can be used as a tool to measure or optimise the ε_{cm} at a work station. Although this tool is presently limited to the conditions described in the investigation, a simple chart (or calibration curve) can be developed to rate the performance of a type of diffuser. Figure 5.7 shows a simplified chart with the measured and predicted ε_{cm} as a function of diffuser flow rate. The data shown are the results for category C (Ts is constant, one central diffuser) and the right side of the graphs indicates the range of values of ε_{cm} measured during the field demonstration.

The curves on the figure show the expected average, maximum and minimum values of ε_{cm} for the one diffuser case. The average value of ε_{cm}, as a function of q, is shown as a dark solid curve and corresponds to values obtained using a 2^{nd} order polynomial approximation. The maximum and minimum ε_{cm} curves shown are drawn by using the outer edges of the 5% error bars for ε_{cm} and q.

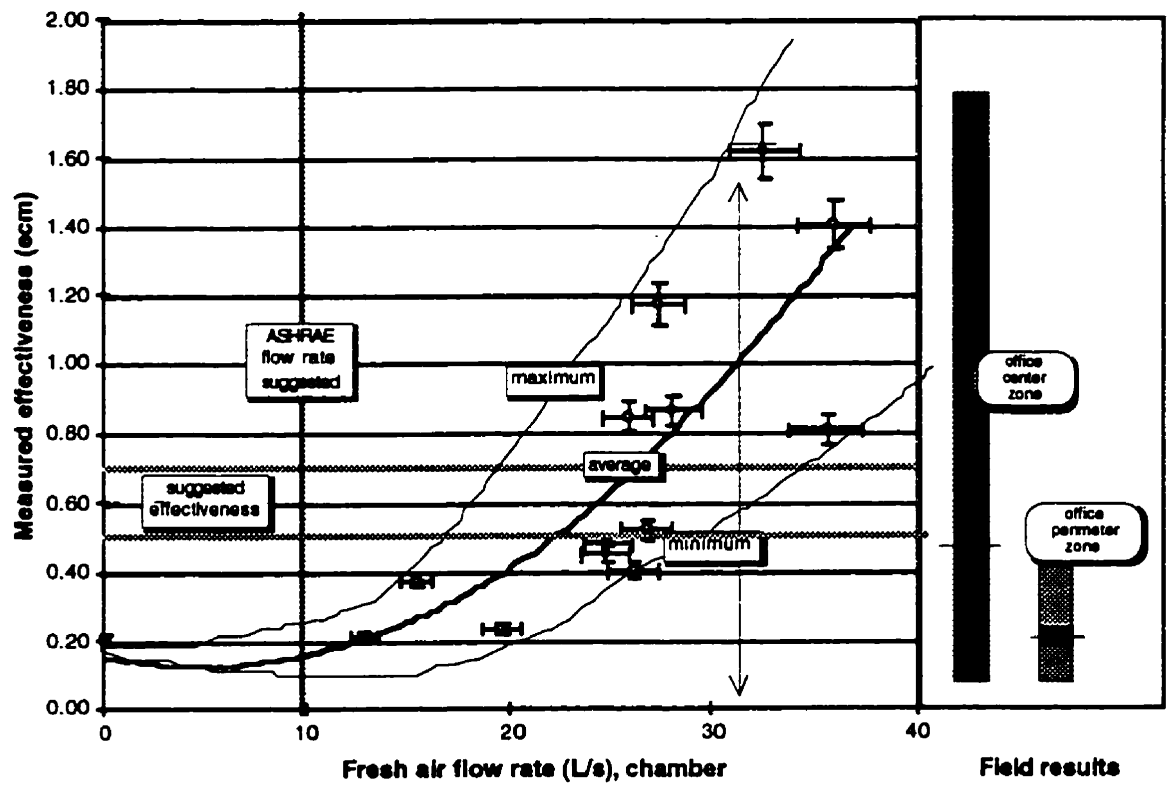


Figure 5.7: Example of application of the method to evaluate the performance of diffusers

As shown, the minimum q prescribed by ASHRAE is not sufficient with one diffuser to obtain ε_{cm} values much higher than 0.20 and, therefore, the q should be increased if the ε_{cm} is to be improved. This is assuming, that ΔTs remains relatively constant and only one diffuser is used.

Since there is not a value of ε_{cm} prescribed by ASHRAE the design question is to decide by how much should the ε_{cm} be increased to satisfy people's outdoor air requirements? Assuming that the ε_{cm} predictions used here are used, should the maximum, the minimum or the average predicted ε_{cm} be used? On one hand, a maximum ε_{cm} may not be desired if this introduces higher Va that will affect thermal comfort negatively. On the other hand, the use of minimum ε_{cm} curve would introduce the opposite problem of not providing a fresh and pleasant atmosphere with low air velocities that could be associated with low ε_{cm}.

What is suggested in the chart is to aim for ε_{cm} values between the minimum and the average values predicted (between 0.5 and 0.6). Based on the chart, ε_{cm} measured in the field could be adjusted to provide an average and a range within the suggested zone. For example, in the perimeter office, controlling the ε_{cm} range to lower values during unoccupied periods could yield energy savings that could in turn be used to provide air-conditioning or humidifying during the day.

Other applications of the ε_{cm} method can be developed based on the charts similar to Figure 5.7 and based on other concepts. For example, assuming that ε_{cm} results could be used for the design of diffusers, a chart similar to Figure 5.7 could be provided by the manufacturers for each of their models of diffusers. Since the ε_{cm} device is automated it can also be installed in different zones of a building to be used for the control the ventilation system. The device could be linked to the existing thermostats and be used for the optimisation of ε_{cm} according to the changing needs of the day. For research purposes, the method can also be used to map the ε_{cm} distribution on the floor of an office building. Finally other ε_{cm} charts could also be developed based on the relationship between perceived air quality and ε_{cm}. Instead of using q as a criteria for ε_{cm}, the ε_{cm} definition for VE could be adjusted to represent perceived IAQ and thus predict human perception as a function ε_{cm}.

These are only some of the applications of the method and more applications can be obtained if the technique is used along with existing CO_2 and other tracer gas techniques. Even though the method was developed for office building conditions, the same approach could be used for the evaluation of the ability of ventilation systems to remove other types of contaminants such as those found in the industry.

6. CONCLUSIONS

From this study, it can be concluded that the ε_{cm} method developed and tested constitutes a valid approach to measure VE for IAQ and energy conservation in office buildings. This conclusion was supported by the results that were obtained during the development and testing of the ε_{cm} method.

Since there is not a standard method for the measurement of VE, validation or verification of a given method for VE can be performed at different levels. Mainly, in this study, the test chamber results and modelling (two-compartment model and regression models) were used to validate the method and obtain the conclusions listed in Table 6.1. Taken together, these conclusions clearly confirm the main conclusion of this thesis that method was adequate for the measurement of pollutant removal effectiveness.

The application of the method permitted to reach further conclusions concerning the principles operating behind process of pollutant removal inside in an office building. These conclusions are listed in Table 6.2. Mainly, experimental results permitted to conclude that air flow rates and air velocities had the most effect on pollutant removal measured using the ε_{cm} method. Also, the relative effect of other room parameters (type of office space, number and location of diffusers, presence mixing fans, temperatures) was established.

From the experimental results obtained in this study, it can also be concluded that the assumptions behind air exchange efficiency methods (ε_a) were not verified in actual conditions. The ε_{cm} results indicated that office spaces, as simulated in the test chamber, do not generally behave as one well-mixed or uniform compartment. This suggests that the VE of a space, as experienced by the occupants, is mostly a function of the local conditions around the worksite. As concluded by other researchers, the measurement of pollutant removal, ε_c, is therefore better suited than ε_a to evaluate VE in actual office buildings. This was also confirmed by the results and the experience gained with the ε_{cm} method in the field.

Further research is required to improve the ε_{cm} method. Mostly, from a practical point of view, the method needs to be integrated into a smaller and more effective CO_2 monitor. This prototype would be able to process CO_2 results and display ε_{cm} results at regular intervals. Assuming that the cost of CO_2 detector continues to fall in the future, other generations of prototypes for ε_{cm} could be developed later. With reduced costs and promises of energy savings, these prototypes could become standard devices for the control of IAQ and energy conservation.

From a theoretical point of view, the most interesting research efforts remaining to be accomplished in VE research would be to verify whether ε_{cm} results can be related to human perception. Human perception seems to be a neglected factor in IAQ studies and there is a tendency to measure IAQ using individual parameters such as q or Va. The value of these parameters are then compared to a standard value assumed to be correct for human comfort. This means that ventilation is evaluated indirectly and without the integration of all the variables actually affecting humans' perception of ventilation. In this sense, every measurement of ε_{cm} can be seen as a series of pictures of the resultant effect of the ventilation on the conditions at a worksite and this representation can be used to evaluate IAQ based on human perception.

Table 6.1: Conclusions regarding the validity of the ε_{cm} method

ε_{cm} results
-varied with diffuser flow rate, q, as expected
-reflected transient changes in the diffuser flow rate, q,
-varied with air velocities, Va, as expected
-were comparable between field demonstration and chamber tests
- were similar to those reported in the literature
- were in accordance with the predictions based on the two-compartment model
-could be modelled using a second order polynomial regression curve with r=0.85 or a linear relation with r=0.77

Table 6.2: Conclusions on VE in office buildings

ε_{cm} in office buildings is expected to be
-be strongly related to air velocities, Va, and air flow rates, q
-vary according to the type of office space
-be affected by the number of diffusers and their locations
-be strongly influenced by mixing fans present
-be affected by air supply and room temperatures over certain ranges
-not be indirectly related to room air temperatures and surface temperatures

7. ORIGINAL CONTRIBUTION TO KNOWLEDGE

The contribution to knowledge of this investigation may be better judged by the obstacles that were surmounted in the course of the development of the ε_{cm} method. The first obstacle surmounted was to provide a clearer and simpler understanding of the concepts used to develop VE methods in a field where fifteen years of research had not yet provided a standard method of measurement. Faced with contradictory results and complicated methods, most researchers could not decide whether VE was a problem in office buildings or whether the techniques they were using were adequate.

Within this context, it was evident that a better technique was needed and the ε_{cm} method was proposed to overcome these limitations. The ε_{cm} method developed was the first method based on the repeated injection of CO_2 used as a tracer gas to simulate human respiration. The results obtained using this method contributed to a better understanding of the basic principles related to the effect of ventilation in office buildings. Also, the demonstration and testing of the technique in an actual building showed that, in practice, the method was far less complicated and less labour intensive than existing methods and therefore, it provided a ready to use tool for practitioners to measure VE in office buildings.

The investigation also contributed to adapt and extend the existing concepts for VE to obtain the ε_{cm} method. The novel approach contributed to the analysis of the process of ventilation applied to the case of a repeated injection of a source of CO_2. This approach pointed to the viability of the ε_{cm} method and other simulation methods for solving the problem of evaluating VE for IAQ and energy consumption in office buildings.

Within the context of indoor air quality and ventilation in general, the method opens the way for more innovations in gas measurement and pollutant removal techniques. From an historical perspective, the ε_{cm} method and similar concepts form an approach that is similar to the old "canary in a cage" method used by miners. While the miners used the bird's "life" as an indicator for carbon monoxide levels in mine shafts, modern techniques such as ε_{cm} allows one to gather large amounts of data with fast and precise instrumentation to simulate a "human in a cage". The response of this "human" is expected to be available for people to measure and understand their environment without risks for their health and comfort. In the long term, this is probably the most important contribution of this study.

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APPENDIX

LABORATORY SIMULATION OF HUMAN BIOEFFLUENTS SOURCES USING CARBON DIOXIDE AS A TRACER GAS

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ABSTRACT

An experimental setup is presented that can measure concentrations generated around a pulsating source of carbon dioxide (CO_2) that simulates human respiration. The experimental setup is used to study the relationship between the ventilation efficiency and the pollutant removal efficiency of a space. These are two key parameters which describe the ability of a space in providing a comfortable and healthy environment for its occupants. Preliminary results obtained so far have focused on the conditions inside a small test chamber. Some preliminary results are presented after a discussion on current tracer gas techniques used in the field.

INTRODUCTION

Current tracer gas methods fail to quantify the ventilation efficiency (VE) of an office space in real conditions of occupancy (1). This is a failure due to two major limitations involved in any field measurement technique: the scale of the testing site and the time required for testing. To deal with the different sizes of buildings, two types of indices are currently available but are not related to each other yet. There are local indices that can evaluate the ability of ventilation to dilute a source at a worksite and there are global indices that can describe the overall mixing of the room where the worksite is located. Transient methods that incorporate a time variable to account for building ventilation schedules, occupancy or pollutant sources are still at the experimental or modelisation stage.

During the thermal comfort studies of the 70's similar limitations were encountered when an index was sought to rate the indoor thermal environment for human occupancy. One index, the Predicted Mean Vote index, was eventually incorporated into a portable instrument that simulated the heat transfer between a sedentary human being and its immediate surroundings (2). Based on assumptions and equations concerning human heat transfer mechanisms, it was able to guess how a person felt thermally and register a vote. Because of its ease of use and because it could be left in a space for several days, this instrument provided a reliable tool to assess a thermal environment without perturbing normal activities or influencing the way a building is operated.

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This presentation describes how a similar instrument can be developed for the evaluation of the indoor air environment in office buildings. Before the method and some preliminary results are described, we will review some of the existing research that deal with air movements in buildings.

LITERATURE REVIEW

During the renaissance Leornardo Da Vinci was fascinated by the observation of the patterns created by moving water. In reviewing his notes, one comes across two small drawings showing a simple experiment he performed in a channel. A paddle, that he called a mobile, was lowered into the stream at two different heights In one case, the water is shown smooth and laminar while, in a second case, the water is disturbed and turbulent. He concluded that the movement and therefore the disturbance in the water was proportional to the movement of the mobile. Da Vinci was concerned with these problems while developing the plans for various waterworks projects.

Today, researchers use tracer gas techniques as a mobile to determine the movement of air in buildings. These tests are performed to assess the quality of the mixing of a space to verify if the ventilation is able to dilute and evacuate indoor pollutants. By injecting a gas in the air, the air movements can be traced for quantification and the air flow patterns can be qualified. Over time, if air travels correctly within an office, pollutants and fresh air will be carried along the stream forces imposed by the ventilation at a rate sufficient to satisfy comfort and health in the breathing zone of a worker. Unlike water in a channel however, the immediate effect of building ventilation over a source is difficult to observe visually because the process is fast and it varies constantly. To be able to see this process accurately, experiments must be repeated at a rate close to the rate of change of the air in the room and the rate of change of the events occurring in an office.

Since this is not practical, existing methods for measuring pollutant removal and VE use averaging techniques to reduce the need to sample frequently. The air change rate of a space can be measured by using the average decay rate of a gas over a period of a few hours (3). When observing a graph of the concentration changes versus time, the results will show a smooth exponential curve with a constant slope. Some methods, such as the mean age of air, use the area under the decay curve to quantify VE (4). Other techniques involve the injection of a tracer to simulate a pollutant and express efficiency by comparing the average concentration measured and the average rate of injection of the pollutant (5,6).

TEST CHAMBER AND DATA COLLECTION

A schematic of the test chamber and part of the data collection equipment is shown in Figure 1.

Tests are conducted in 64 m^3 room that has its independent ventilation system. The supply fan of the system is linked to a controller that can vary the speed of the motor and provide between -100 and 200 L/s of air. The controller can be activated by a relay to simulate on-off cycles and, the controller can be set to ramp (reach maximum speed) in different time periods. A return fan completes the 'H' type of design that allows variation of the evacuation, return and fresh air flow rates.

Presently, the room simulates an interior zone, unoccupied, equipped with four fluorescent lamp fixtures (320W) and the exterior surfaces of the room are maintained at constant temperature. These conditions can be changed to simulate different scenarios typical of an interior zone of a building with one or two occupants. The room is equipped with two separate injection lines for CO_2 and sulphur hexafluoride (SF_6).

The CO_2 line (see Figure 2) can be used to deliver pure CO_2 or a gas mixture of air and CO_2 at 740 ppm. Injection is performed at a height of 0.6 m in the center of the room to simulate a seated person. All the volumes of gas are measured and adjusted using a rotameter or a precision bubble flowmeter. The solenoid valve at the end of line is activated by a relay controled by a timer to create pulses at intervals and durations between one second and 24 hours. CO_2 data are collected in the center of the room by a direct reading instrument with a passive infra-red detector. The detector has a precision of 50 ppm for readings up to 2000 ppm and of 100 ppm for higher readings. Concentrations can be obtained every 8 seconds and can be transferred to a computer for data analysis.

The SF_6 line sends pure SF_6 at the fresh air intake of the supply fan. This line is also activated by a relay and controled by a timer. SF_6 data are collected using a portable photoacoustic gas detector and samples can be collected at twelve different locations in the room. The shortest sampling rate is approximately 40 seconds and the detection limit is 0.05 ppm. Depending on the number of locations required for sampling, different sampling points can be selected using a twelve way valve activated by a relay and controled by a timer.

Air volumes going into the room can be measured in three different ways. A pressure grid located in the main duct of the ventilation system provides a pressure reading proportional to the airflow across the grid and this is measured with a pressure gauge. The ventilation airflow can be measured at either one of the three diffusers in the room using a balometer. Finally, air changes per hour can be measured using an SF_6 tracer gas decay.

PRELIMINARY EXPERIMENTS AND RESULTS

Preliminary testing was performed to find the correct injection method to obtain a good response from the CO_2 monitor at ventilation rates typical of infiltration in an office building. Results in Figure 3 show measurements of two series of CO_2 pulses labeled as pulses P1 and P2. Both have a duration of 2 minutes and were reproduced at 20 minute intervals. The average rate of injection was set to 0.3 Lpm for P1 (close to human respiration rate) and to 0.1 Lpm for pulse P2. For both pulses, the injection rates varied in the first seconds of the injection period and initial flow rates were approximately 20% above the final constant injection rate. This was due to the long length of the injection line and initial pressure buildup in the line in between the pulses. The measurements shown were performed after 8 hours of constant injection to allow background concentrations in the room to stabilize. Infiltration in the room was measured to be constant at 0.37 air changes per hour using a tracer gas decay test.

DISCUSSION OF RESULTS

Table 1 shows a summary of the results obtained. The ratio of the maximum concentration of pulse P1 over pulse P2 is 2.6 and is close to the ratio of 3 for the average injection rate of P1 over P2. Since the number of measurement is high, the area under the curve of the pulses can be estimated by summing all the concentrations in time. If we correct the concentrations of P2 and add to them the difference between the minimum concentration of P1 and the minimum concentration of P2, we obtain a corrected pulse, P2*, as shown in Figure 4. The corrected pulse allows us to compare the area under the two pulses irrespective of the background concentration in between pulses and a ratio of 1.5 is obtained if divide the area under P1 by the area under P2.

CONCLUSION

At this stage, preliminary results indicate that the method discussed here is able to measure and approximate reasonably well the dilution process occurring in the test room. The next step will be to sharpen the profile of the injection pulses and, to repeat the same measurements with higher ventilation rates to obtain data for dilution as a function of ventilation. The method will also have to be tested for various space layouts and to account for the presence of other carbon dioxide sources in the room. After these results will be available, it will be possible to simplify the method further by determining the optimum sampling rate required to describe the pulses accurately.

ACKNOWLEDGEMENTS

This work is supported in part by the contribution of the Institut de Recherche en Santé. et Sécurité du Québec (IRSST). We would like to thank Bob Robb, chief technician for McGill's Occupational Health Department for his contribution to the test chamber.

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TABLES AND FIGURES

Table 1: Comparison of pulse P1 and P2

Parameter	units	P1	P2		Difference P1-P2	Ratio P1/P2
Average injection rate	Lpm	0.3	0.1		0.2	3
Maximum	ppm	4561	1788		2774	2.6
Minimum	ppm	622	433		189	1.4
Average	ppm	1197	633		564	1.9
Sum of concentrations	ppm	1.08E+06	5.72E+05	*	5.09E+05	1.9
Adjusted sum	ppm	1.08E+06	7.42E+05	*	3.38E+05	1.5
Number of observations		903	903			

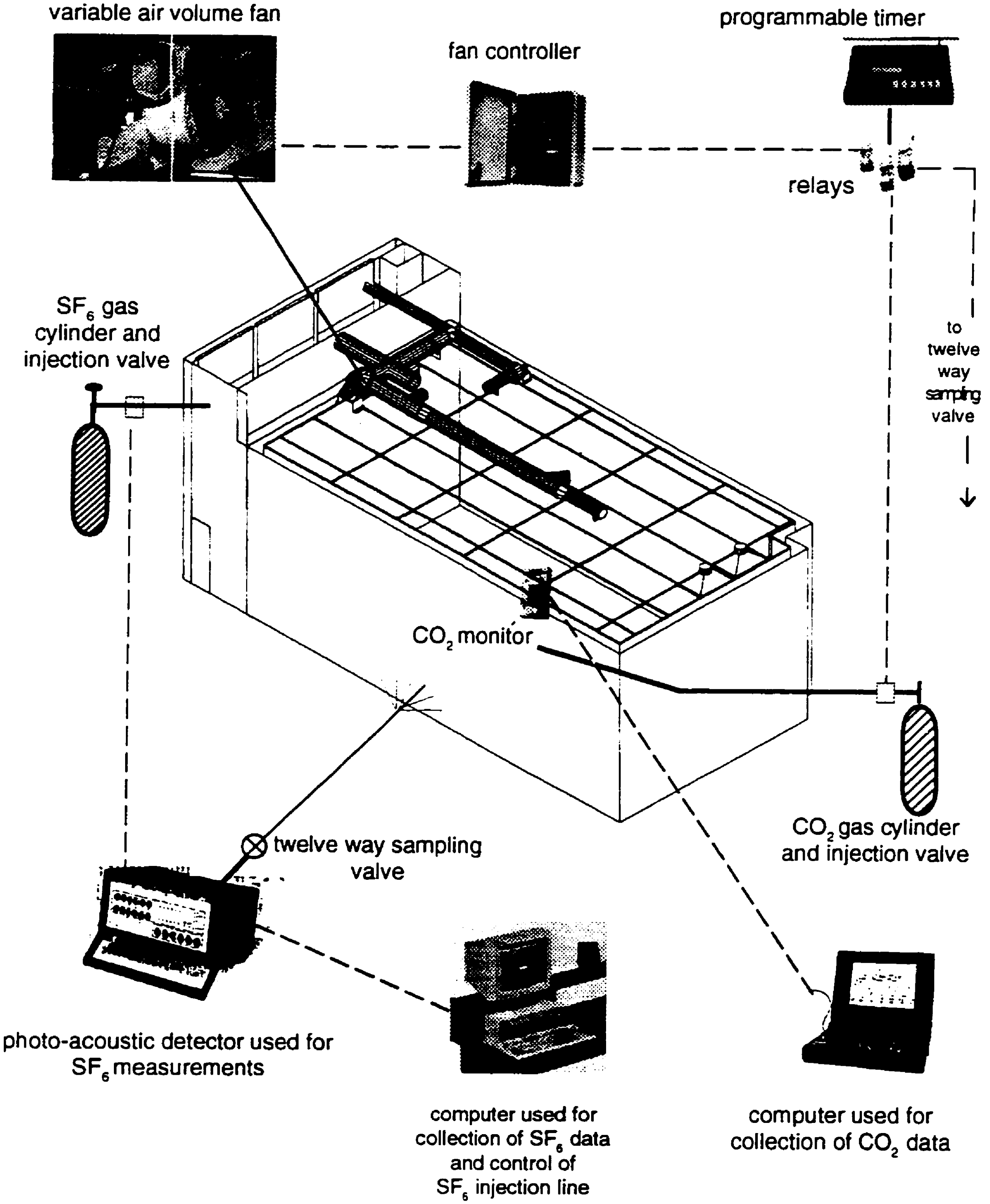
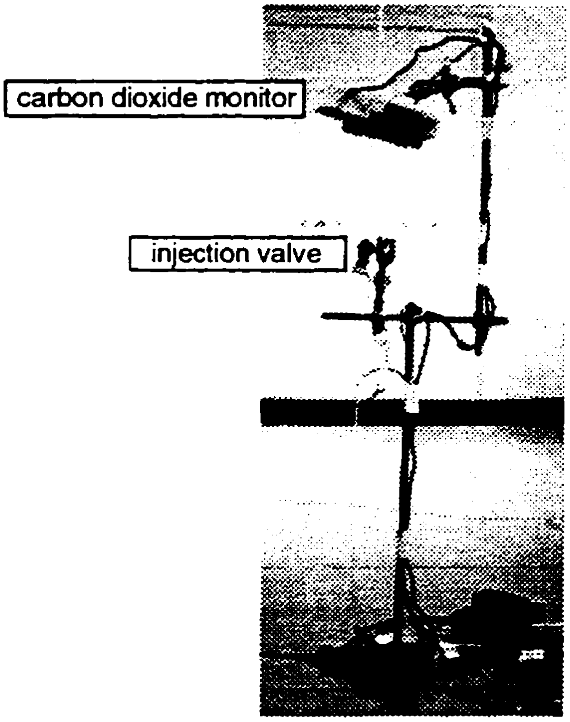
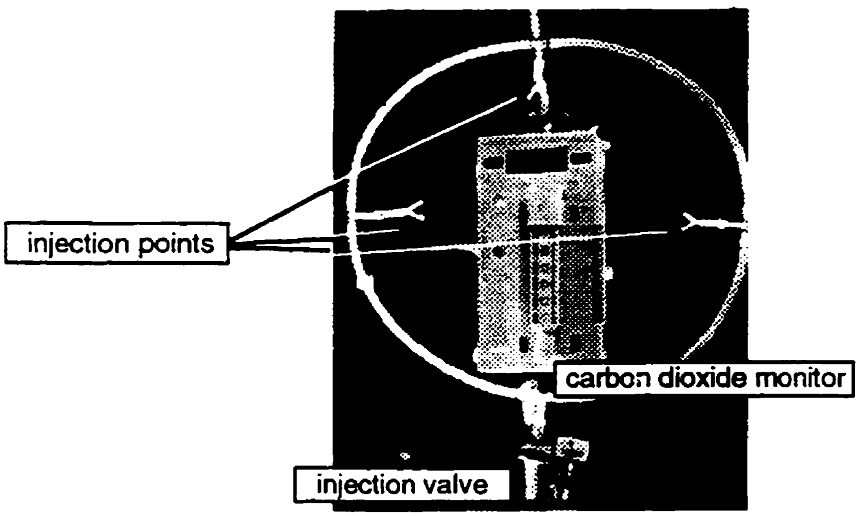


Figure 1: Data acquisition and injection systems

Martin Auger-McGill, 1994



a) injection tripod



b) injection system with circular diffuser (front view)

Figure 2: Injection system for carbon dioxide

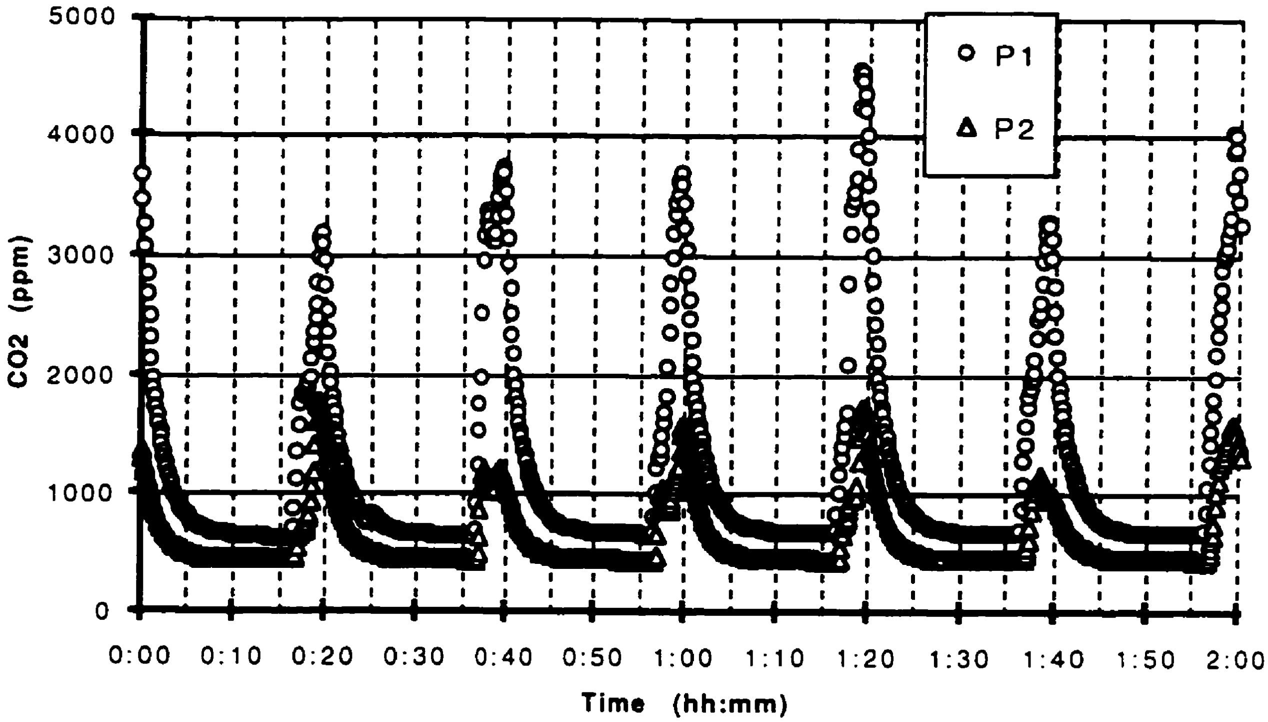


Figure 3: Concentrations of CO_2 measured over two hours for pulses P1 and P2

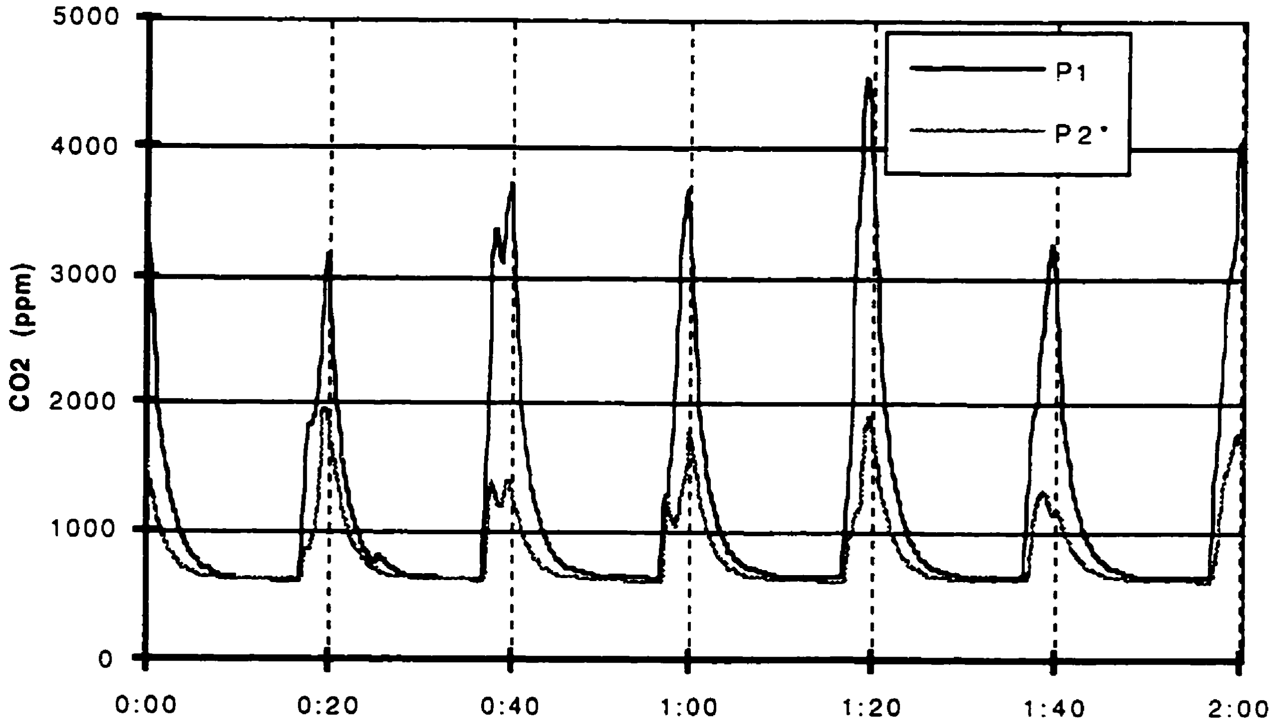


Figure 4: Pulse P2 modified for background concentrations

MEASUREMENT OF DILUTION VENTILATION EFFICIENCY USING CO_2 AS A TRACER GAS. M.R. Auger and J.P. Farant, McGill University, Department of Occupational Health, Environmental Laboratory, F.D.A. room 24, Montreal, Quebec, Canada, H3A 2A7.

ABSTRACT

Ventilation efficiency (VE) describes the ability of a ventilation system to distribute outdoor air and remove pollutants in a room. Although VE is an important parameter for IAQ and energy conservation, few methods allow to measure this parameter. Techniques developed for the measurement of VE involve the use of a tracer gas. The proposed measurement technique involves the use of an accepted tracer gas, CO_2, that is injected in a room to simulate human respiration. The method was tested in a $64m^3$ control chamber where temperature, humidity, air velocity and air flow rates were adjusted and controlled. The measurement method performed well under test conditions as shown by the relationship between VE and diffuser flow rates (r^2>0.95). Compared to other methods, this technique is simpler, less labour intensive and does not require complex assumptions concerning the air flow patterns in a room.

INTRODUCTION

Ventilation efficiency (VE) is a relatively new concept that describes the ability of a ventilation system to distribute outdoor air and remove pollutants in a room. VE is an important parameter for indoor air quality (IAQ) in office buildings since it can be estimated that roughly 80% of complaints for air quality are related to ventilation and specific pollutants(1). Also, the most important standards on ventilation for IAQ such as the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) in the United-States specify IAQ in terms of outdoor air flows and control of pollutants and include correction factors to compensate for poor VE (2).

Although VE is an important parameter for IAQ and energy conservation, the problem has remained the question of how to measure this parameter in actual conditions of operation normally encountered in office buildings. This is why a new technique was developed in a test chamber to provide a simple and accurate method to measure VE in office buildings. In the reminder of this presentation the technique developed is presented as well as the results obtained following its application under controlled conditions. Before the method is presented, a short description of the existing methods is presented.

TRACER GAS TECHNIQUES AND VE

All the techniques developed for the measurement of VE involve the use of tracer gas. With these techniques, a tracer gas is injected into a room to label the outdoor air to study its distribution or, the tracer gas is used to simulate a pollutant source to study the dilution and dispersion of the gas into a room. For air distribution, the techniques involve the concept of "age-of-air" and for pollutant removal, the techniques involves simply the concentrations of the pollutant simulated by the tracer gas.

One of the first technique developed in the 1980s to measure VE for outdoor air distribution, ε_a, was the "age-of-air" technique.(3) This technique is based on the definition of the "age-of-air" as the time since a molecule of gas in the air has entered the room. Under this definition, the "youngest" air is the air entering the room while the "oldest" age is assigned to the air leaving the room. The efficiency is obtained by comparing the tracer gas concentrations to the predicted concentrations using the ideal flows shown in figure 1. In theory, the best air distribution that can be obtained in a room is for piston-flow (a) or perfect mixing (b). In between these two cases, "short-circuiting" is the worst condition obtained when part of the air is not reaching the zone of occupancy and is evacuated directly. Piston flow is the best flow configuration able to ventilate the air in a room and is twice as fast as the perfect mixing case. However, in piston-flow, there is chance that the pollutants will be in highest concentrations near the exhaust and this may affect the occupants.

As seen in figure 1, the ability of a ventilation system to dilute pollutants, ε_c, is not only dependant on the overall room air distribution but it is also dependent on the location and type of source present in the room. This is why "pollutant removal" techniques are usually based on using a tracer gas to simulate a pollutant source and measure the dilution of this source directly into the space using the concentrations of the gas. Some techniques are based on the occupant-generated carbon dioxide (CO_2) that is already present in the room and pollutant removal is calculated by dividing the concentrations in the room by the concentrations in the exhaust of the ventilation. Other techniques have involved the simulation of pollutants using tobacco smoke from cigarettes or using perfluorocarbons sources distributed into a room.

Most of the existing techniques used to measure VE have been successfully applied in controlled test chambers but have failed to perform well in actual office buildings. One of the main failure for the techniques has been the use of a tracer gas that is not readily accepted by the occupants such as refrigerant gases (R-12) or the use of toxic or anaesthetic gases (sulphur hexafluoride, nitrous oxide). Another limitation is that most of the theoretical models (piston-flow or perfect mixing) used to calculate VE are too simple to predict field conditions correctly. Finally, because the measurement apparatus are usually too complex and elaborate, the application of the techniques in the field is reserved to specialised teams and are not easily understood by practitioners.(4)

MEASUREMENT TECHNIQUE

The proposed measurement technique has been designed to overcome the limitations of the existing measurement techniques for VE. The method proposes the use of an accepted tracer gas, CO_2, that is injected in a room to simulate human respiration. Both injections of CO_2 and measurement of the resulting concentrations is performed by an automated system that is simply placed at the worksite where VE is to be measured. Although this technique is mainly used to evaluate pollutant removal, ε_c, it also evaluates ε_a indirectly since ε_a and ε_c can be assumed to be related. The measurement system and the test chamber used to develop the system are presented in the following.

The measurement system developed for the method is shown in figure 2. The injection system is designed to generate a pulse of CO_2 lasting 4 minutes towards a monitor (*model YES-203, Young Environmental Systems, Vancouver, Canada*) recording the concentrations at 16 seconds intervals. The pulse is repeated every 20 minutes at a 0.9 meter height and at a flow rate is 0.3 L/min. This flow corresponds to the CO_2 generation rate of a sedentary, seated human being. The 4 minute injection time was selected because this time is longer than the response time of the monitor (measured at 2.4 minutes for 95% response) and because this duration is short enough to prevent accumulation of CO_2 in the room.

The value of ε_c is calculated by using the concentrations before the pulse (C_0) and the maximum concentration (C_{max}) obtained during the pulse. The formula used to calculate the efficiency is the following (5):

$$\varepsilon_c=100/(C_{max}-C_o)$$

This expression is obtained by assuming that under perfect conditions, ε_c is maximum when the source of CO_2 is completely diluted by the ventilation. In other words, for maximum pollutant removal, the concentrations around the source (C_{max}) should be equal to background concentrations in the room (when $C_{max}=C_0$, ε_c is infinite). This expression can also be obtained using the predictions from a two-chamber model such as the one used by ASHRAE to predict steady-state pollutant concentrations resulting from a known source and ventilation rate (2). The factor of 100 is used to bring ε_c values between 0 and 1.0 and takes into account the limit of detection of 100 ppm of the CO_2 monitor.

The method was tested in a 64m^3 control chamber where temperature, humidity, air velocity and air flow rates were adjusted (see figure 3). Tests were performed with flow rates of outdoor air varying from 20 L/s to 80 L/s and for air distribution through the central, four-way, square diffuser. These cases were selected to simulate actual room conditions found in office buildings where ASHRAE recommends a minimum of 10 L/s per person of outdoor air. In these cases, the flow above 10 L/s (21 ft^3/min or cfm) is assumed to be necessary to distribute the outdoor air into the room.

RESULTS

The results obtained for CO_2 concentrations (one typical case) in time and ε_c as a function of diffuser flow are presented in figure 4 and figure 5 respectively.

Figure 4 shows typical CO_2 concentrations obtained following the repeated injections in the room for an airflow rate of 55 cfm. As can be seen, the concentrations rise during a pulse and fall back to background levels after the injection is stopped. For each pulse, ε_c is calculated using the formula described above and yields 3 values per hour.

Figure 5 shows the result of ε_c as a function of diffuser flow varying between 27 and 82 cfm (13 and 38 L/s) in the test chamber. Three lines show the regression obtained for ε_c as a function of diffuser flow and each line differs by the number of concentration peaks used to calculate ε_c. In the first line, C_{max} is the average of the two maximum peak concentration values observed during the measurement period. The other two lines use the average of three and four maximum values respectively as they are obtained by classifying the peaks in decreasing order.

The selection of the number of maximum values was performed to establish the effect of averaging on the ε_c results. As seen in the figure the r^2 value (coefficient of determination) is affected by the number of peaks included in the calculations. With two maximum values, the r^2 is 0.91 for ε_c as a function of flow rate and, r^2 is 0.95 for three maxima. Overall, the r^2 is the highest if three peaks are included and it progressively decreases as more peaks are added (not shown) in the average used to calculate C_{max}. This means that the method for measuring ε_c can be based on the average of two peaks occurring within forty minutes.

CONCLUSION

The measurement method for ε_c performed well under test conditions as shown by the relationship between ε_c and diffuser flow rates ($r^2>0.95$). Compared to other methods, this technique allows to circumvent some of the limitations of found in the measurement of VE in the field. First, the method uses a tracer gas, CO_2, that is readily accepted by occupants since it is already present in the indoor air. Second, the technique is relatively simple to use since it is automated and does not involve a complicated analysis of the results. Finally, the method is easy to understand since it does not make any complicated assumption concerning the overall flow pattern of the air in the room: what is measured is simply the response that would be obtained if a person was actually located in a room. Further testing (not presented) has also shown that the method is able to respond well to other ranges of flow rates and to different diffuser layouts in the room and was also applied successfully in an actual building. The method can also be adapted to perform measurements in other types of environments such as in industrial settings to evaluate the dilution of other types of pollutants.

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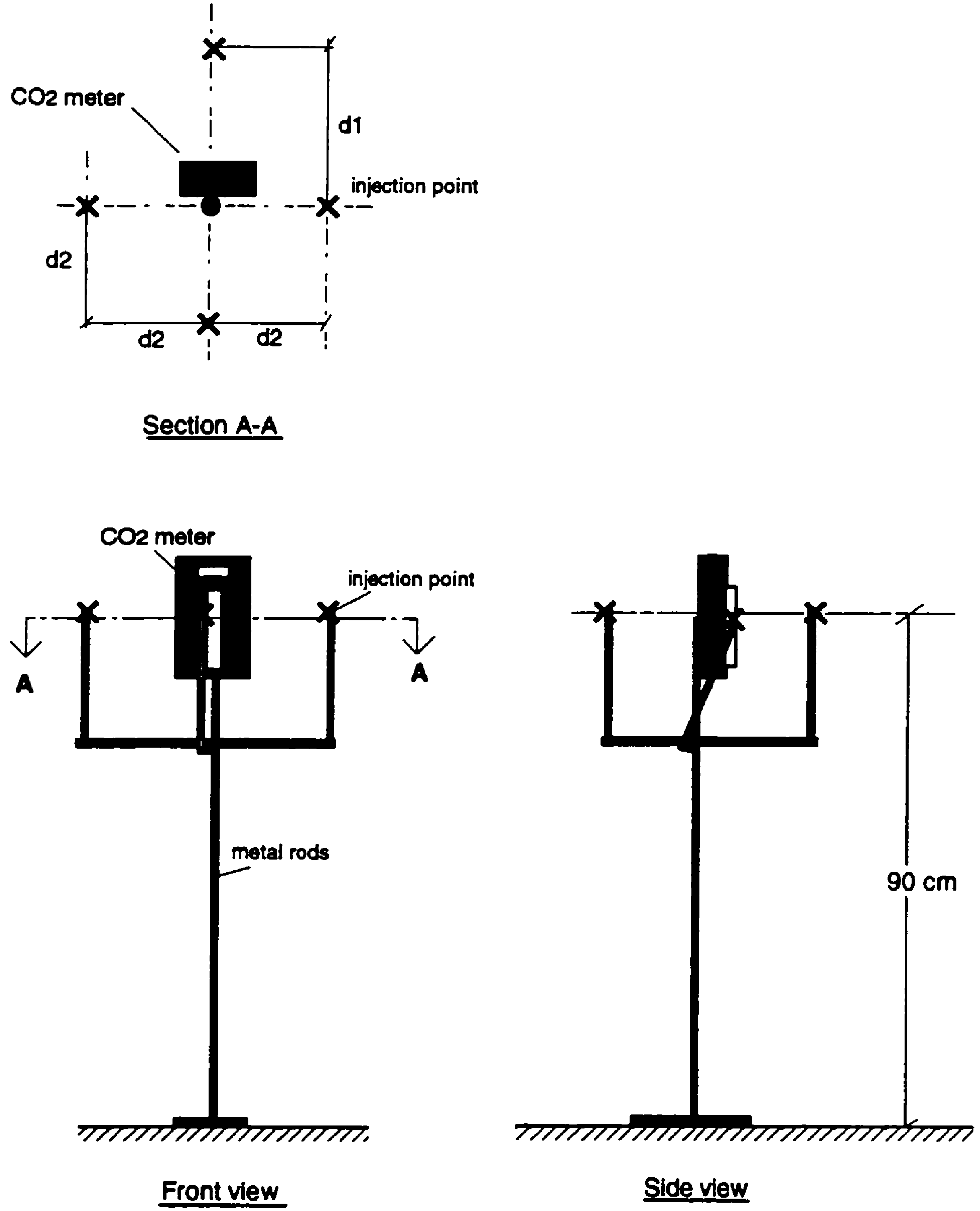

Figure 2: Injection and measurement system

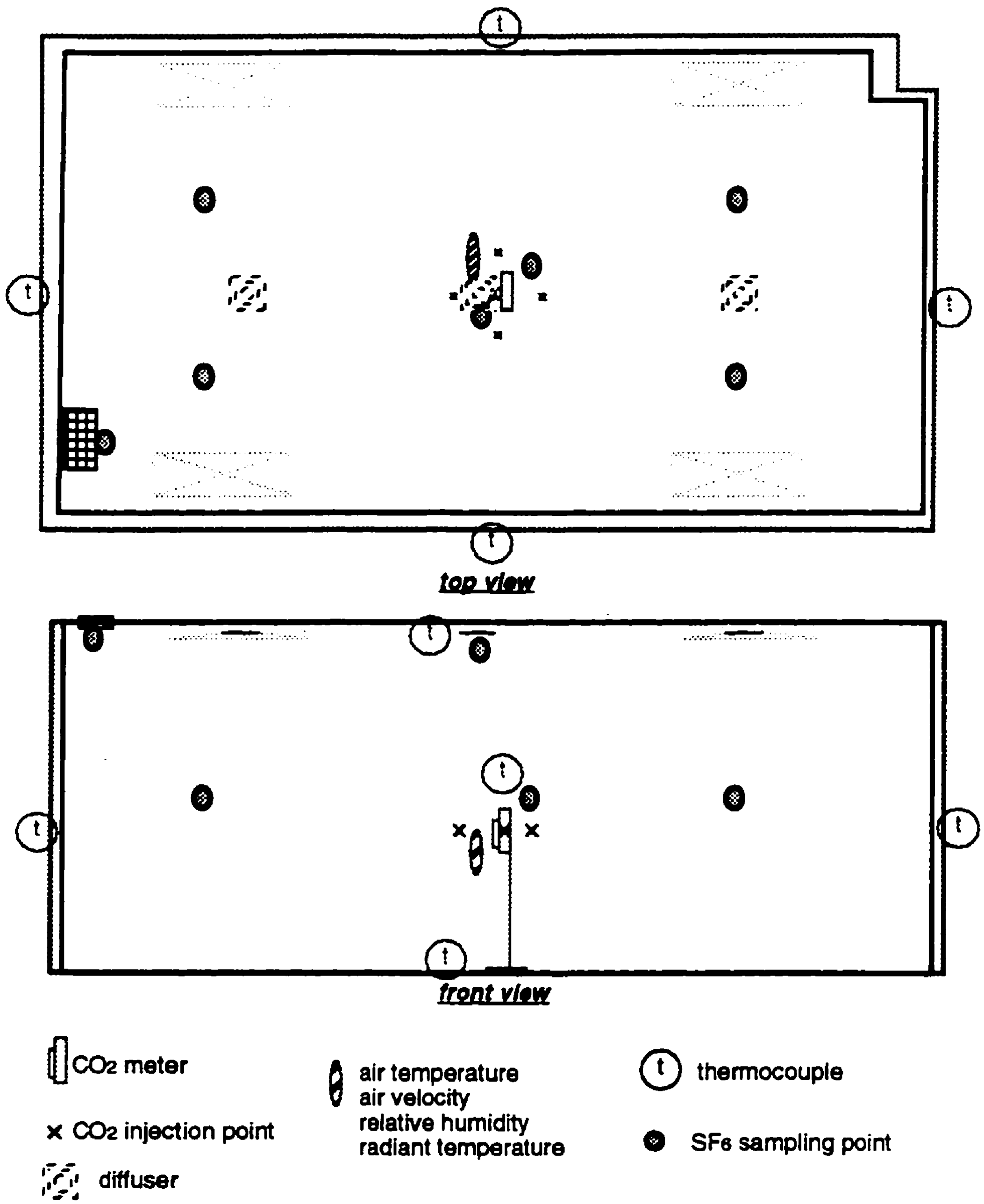

Figure 3: Test chamber and instrumentation

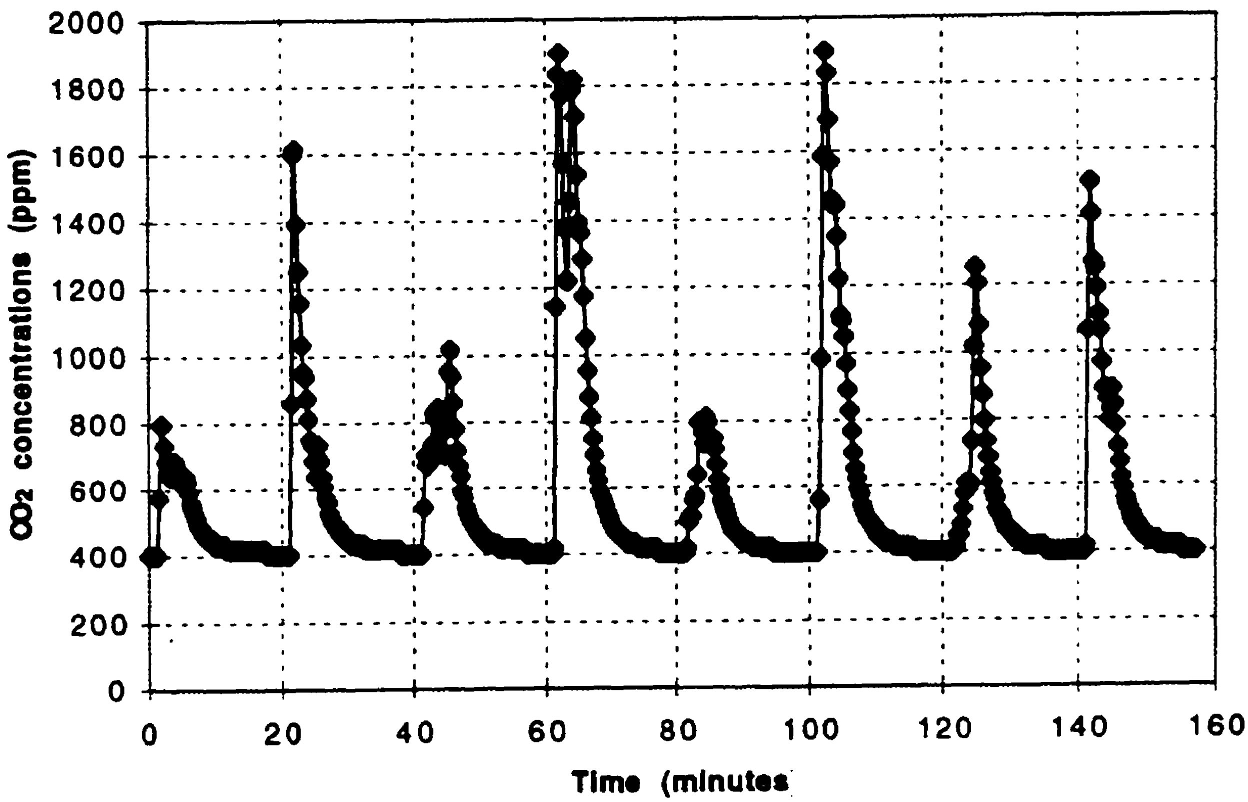

Figure 4: CO2 concentrations as a function of time

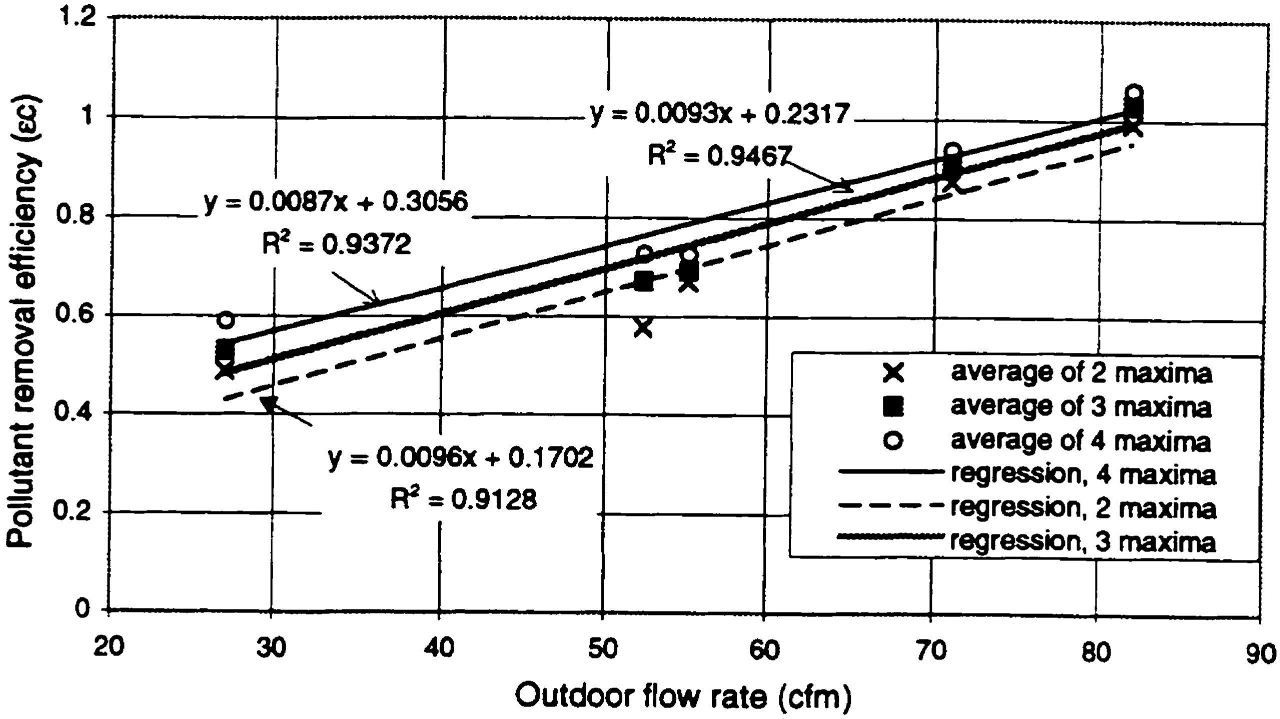

Figure 5: Efficiency as function of diffuser flow

Méthode pour la mesure de l'efficacité de ventilation dans les édifices à bureaux

par Martin Auger et Jean-Pierre Farant [1]

RÉSUMÉ

L'efficacité de ventilation évalue la capacité d'un système de ventilation à distribuer de l'air et à enlever les polluants. Ce paramètre est important car environ 80 % des plaintes rencontrées dans les édifices sont reliées à la ventilation et aux polluants. Le standard ASHRAE 62-90 recommande un débit de ventilation de 10 L/s/personne d'air neuf. Cependant, ce débit doit être augmenté si l'air n'est pas distribué efficacement. Une nouvelle méthode a été développée en laboratoire pour mesurer l'efficacité en simulant la production de CO_2 par les occupants. La méthode consiste à injecter 0.3 L/minute de CO_2 vers une sonde de CO_2. Ce taux est le taux moyen de génération de CO_2 d'un être humain effectuant un travail sédentaire. L'efficacité est calculée par la différence entre la concentration maximale mesurée pendant l'injection et la concentration mesurée avant l'injection. Des résultats sont présentés pour des écarts de température de soufflage de 6 °C et 9 °C, des vitesses de l'air de 0.07 m/s et 0.45 m/s et un débit de ventilation fixé à 10 L/s. L'efficacité a varié par un facteur de 1.5 pour les températures de soufflage et par un facteur de 6 pour les vitesses de l'air. Comme la méthode diffère des méthodes existantes, les résultats se comparent de façon indirecte avec les résultats d'autres chercheurs. On conclut que la méthode est sensible aux conditions de mélange et que des essais supplémentaires devront être effectués en variant les débits de ventilation. La méthode a l'avantage d'être facile d'utilisation sur le terrain.

Mots clés: efficacité de ventilation, qualité de l'air, gaz traceurs.

ABSTRACT

Method for the measurement of ventilation efficiency in office building.

Ventilation efficiency evaluates the ability of a ventilation system to distribute the air and dilute pollutants. This parameter is important since roughly 80% of complaints in buildings are related to ventilation and pollutants. The ASHRAE standard 62-90 recommends 10 L/s/person as an acceptable value for fresh air supply to occupants. This rate however must be increased if the air is not distributed adequately. A new method has been developed in a test chamber to measure efficiency by simulating the CO_2 production from the occupants. The method consists in a 0.3 L/minute injection of CO_2 towards a CO_2 monitor. This corresponds to the average production rate of CO_2 from a sedentary human being. The efficiency is calculated by taking the difference between the maximum concentration obtained during the injection and the concentration before the injection. Results are presented for room/supply temperature differences of 6 °C and 9 °C and for air velocities of 0.07 m/s and 0.45 m/s. In all cases, the ventilation rate was fixed at 10 L/s. Efficiencies varied by a factor of 1.5 for supply temperature changes and by a factor of 6 for air velocities. Since the method is different from existing methods, results are compared on a relative basis. It is concluded that the method responds to the mixing conditions in the room and that additional work is to be done by varying the air flow rates. The method has the advantage of being easy to use and can be easily applied in field conditions.

Key words: ventilation efficiency, air quality, tracer gas.

INTRODUCTION

L'efficacité de ventilation est un paramètre qui décrit la capacité d'un système de ventilation à distribuer de l'air dans les édifices à bureaux et à en enlever les polluants. Ce paramètre est important si l'on considère que plus de 80 % des plaintes rencontrées dans les édifices sont reliées à la ventilation et aux polluants (*1*). Malgré son importance, la mesure de l'efficacité de ventilation dans des conditions réelles d'occupation ne fait pas encore l'objet d'un standard. Une revue de littérature effectuée en Europe conclut que les méthodes actuelles sont trop compliquées et inutilisables sur le terrain et que des recherches sont nécessaires pour développer des méthodes s'appliquant aux conditions existant réellement dans les espaces à bureaux (*2*).

Le présent article décrit une méthode simple de mesure de l'efficacité de ventilation qui est automatisée et peut être utilisée sur le terrain. La méthode a été développée en laboratoire dans une chambre contrôlée. Elle consiste à mesurer la réponse d'un moniteur à des injections répétées de dioxyde de carbone (CO_2). Ces injections de gaz permettent de quantifier l'effet de la ventilation sur une source de bio-effluents humains. Cette méthode est décrite ainsi que les résultats obtenus pour trois scénarios de ventilation. Avant de décrire la méthodologie les techniques de mesure existantes et les modèles de distribution de l'air utilisés pour développer la méthode sont discutés. L'article conclut sur la performance de la méthode et l'impact des résultats préliminaires sur les travaux à venir.

Le standard ASHRAE 62-90 prescrit un débit de ventilation minimal de 10 L/s/personne d'air neuf (air extérieur) pour une occupation normale de 7 personnes par 100 m^2 (*3*). Pour répondre aux besoins de climatisation d'un espace avec des travailleurs et des équipements de bureaux, le débit d'air total sortant des diffuseurs inclut environ 80% d'air recirculé et 20 % d'air neuf. Comme le mentionne le standard, ces débits doivent être augmentés si l'air n'est pas distribué efficacement aux différents zones de travail en raison de facteurs comme l'aménagement des bureaux, la position et le nombre de diffuseurs et la stratification de l'air. Cette augmentation peut être calculée en mesurant l'efficacité réelle de la ventilation à l'aide de différentes méthodes.

Les méthodes existantes de mesure de l'efficacité de ventilation font référence à trois scénarios typiques de distribution de l'air: mélange parfait, déplacement par piston et court-circuitage. En pratique, le déplacement de l'air observé dans une pièce sera une combinaison de ces cas mais, ces profils peuvent être utilisés comme point de départ pour une analyse qualitative des mouvements de l'air. Dans le cas d'un mélange parfait (figure 1a), tous les points de la pièce ont le même taux de ventilation et les polluants sont dilués également dans l'ensemble de la pièce. Avec un déplacement par piston (figure 1b), le taux de ventilation est le même partout et la dilution des polluants dépend de la position des sources de polluants dans la pièce. Finalement, dans une situation de court-circuitage (figure 1c) l'air circule surtout dans une portion de la pièce et les polluants s'accumulent dans les zones stagnantes. Ces trois scénarios peuvent être étudiés sur le terrain à l'aide d'essais de fumée, des mesures de vitesse de l'air ou avec un gaz traceur.

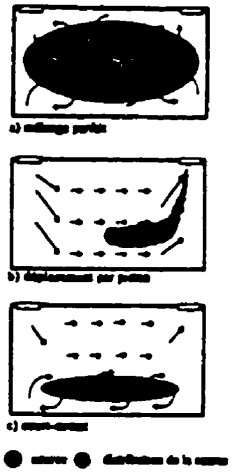

Figure 1. Modèle de distribution et de dilution.

La plupart des techniques de mesure de l'efficacité utilisent des gaz traceurs pour mesurer la distribution de l'air et la dilution des polluants. L'efficacité est calculée en comparant les concentrations mesurées avec

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les concentrations qui auraient été obtenues pour un mélange parfait ou un déplacement par piston. L'efficacité est inférieure à 100 % si la distribution de l'air et la dilution des polluants observés tendent vers un mélange avec des court-circuits. Les équations utilisées pour ces techniques sont décrites en détail dans la littérature et ont été appliquées en laboratoire et dans des édifices (*4,5*). La revue des méthodes effectuée par Fisk (*5*) montre que sur le terrain les estimés obtenus par les méthodes actuelles ont une erreur systématique d'environ 20% car elles ne tiennent pas compte de l'infiltration de l'air extérieur et des changements des horaires de ventilation.

MATÉRIEL ET MÉTHODES

La méthode consiste à mesurer l'efficacité de dilution de la ventilation en simulant la production de CO_2 par les occupants. Cette méthode est semblable à d'autre méthodes proposées pour simuler la dispersion des polluants comme la fumée de cigarette ou les composés volatils générés dans les édifices à bureaux (*6*). La méthode est appliquée à l'aide d'un système d'injection qui est installé dans une chambre contrôlée. Ces composantes sont décrites ainsi que la formule utilisée pour calculer l'efficacité.

La figure 2 montre le système d'injection et de mesure utilisé pour les essais. Ce système comprend un trépied d'injection qui fournit 0.3 L/minute de CO_2 vers une sonde de CO_2 (modèle 203, Young Environmental Systems, Vancouver, Colombie-Britannique). Ce taux d'injection est le taux moyen de génération de CO_2 d'un être humain effectuant un travail de bureau sédentaire (*7*). Les injections durent 4 minutes et sont répétées aux 20 minutes. Cette technique d'injection permet d'obtenir des mesures répétées sans augmenter la concentration dans l'ensemble de la pièce. La sonde est située face à trois buses d'injections et enregistre les concentrations à 16 secondes d'intervalle. Cette sonde a une précision de 100 ppm et est calibrée à l'aide d'un standard ayant concentration de 734 ppm.

Le système d'injection est placé dans une chambre d'essai équipée d'un système de ventilation indépendant. La chambre expérimentale mesure 6.5 x 3.6 m par 2.75 m de hauteur (voir figure 3). Le système de ventilation peut fournir de 0 à 300 L/s d'air neuf à un, deux ou trois diffuseurs situés au centre de la pièce. Deux ventilateurs portatifs sont placés d'un côté de la chambre et sont activés de l'extérieur. Ces ventilateurs permettent d'obtenir un mélange complet et rapide de l'air et sont contrôlés par une minuterie. La chambre est éclairée par quatre luminaires ayant une puissance totale de 320 W. Pour simuler la chaleur sensible de l'activité humaine, une ampoule de 100 W est placée au centre de la pièce. Les températures des surfaces intérieures et de la ventilation sont mesurées à l'aide de thermocouples. Les débits de ventilation sont ajustés en contrôlant la vitesse du ventilateur et sont mesurés à l'aide d'un balomètre (serie 8400, Shortridge Instruments, Scottsdale, Arizona). Un anémomètre omnidirectionnel (modèle 1213, Brüel & Kjaer, Danemark) mesure la moyenne des vitesses de l'air au centre de la pièce à des intervalles de 5 minutes.

Les calculs d'efficacité peuvent être dérivés à partir des équations de mélange à l'équilibre. Si une quantité de CO_2 est injectée dans un volume d'air mélangé parfaitement, la concentration maximale atteinte à l'équilibre est exprimée par la formule suivante (*8*):

$$C_e = C_i + \frac{F}{Q}$$

où:

C_e: Concentration de CO_2 obtenue à l'équilibre

C_i: concentration de CO_2 avant injection

F: taux d'injection de CO_2

Q: taux de ventilation

Dans des conditions de mélange normales, on obtiendra un débit de ventilation réel ou efficace, Q_{eff}, qui dépend de l'efficacité de ventilation, E:

$$Q_{eff} = E.Q$$

Pour ces conditions, les concentrations à l'équilibre seront exprimées par la formule:

$$C_e = C_i + \frac{F}{E.Q}$$

Pour un taux de ventilation constant et un taux d'injection constant, une efficacité relative de la ventilation, e, peut être définie en simplifiant la formule précédente (*9*):

$$e = \frac{1}{(C_e - C_i)}$$

Selon cette formule, l'efficacité de dilution est inversement proportionnelle à la différence entre la concentration maximale mesurée pendant l'injection et la concentration mesurée avant l'injection. S'il y a une bonne dilution autour du point de mesure, les concentrations maximales sont basses et, si la dilution n'est pas efficace, les concentrations maximales sont élevées. Quand C_e a une valeur proche de C_i, l'efficacité tends vers l'infini. Comme le taux d'injection de CO_2 est toujours le même, la mesure d'efficacité peut être comparée pour divers cas ayant un même débit de ventilation.

Les résultats des mesures de CO_2, des températures et des vitesses de l'air sont présentés ici pour trois cas étudiés dans la chambre expérimentale. Pour ces trois cas, le débit du diffuseur central a été ajusté à 19 L/s d'air neuf ce qui est la quantité d'air neuf prescrite par ASHRAE pour la superficie de la pièce. Pour ces essais, seulement les températures d'alimentation de l'air ont été changées et les ventilateurs de mélange ont été activés pendant deux périodes de une heure. Les diffé-

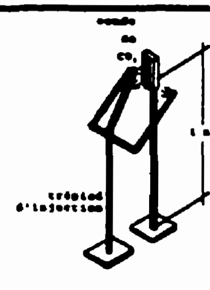

Figure 2. Système d'injection.

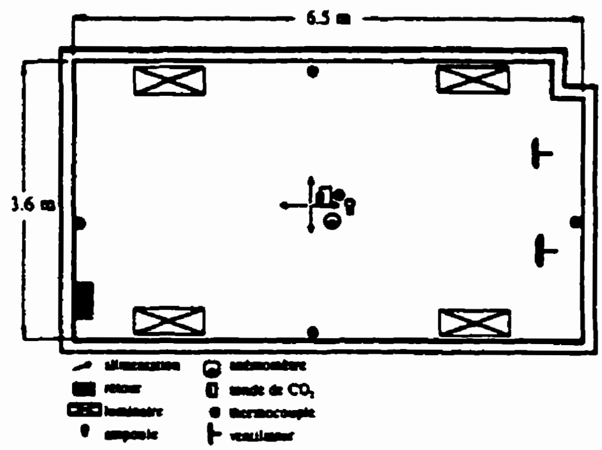

Figure 3. Chambre d'essai et instrumentation.

rences de température ont été créées pour étudier les variations de la dilution obtenue dans la pièce avec différentes conditions thermiques. De plus, la mise en marche des ventilateurs permet d'étudier des conditions dans la chambre qui se rapprochent du mélange parfait et donc d'une efficacité élevée.

RÉSULTATS

Les conditions mesurées dans la chambre pour les trois cas étudiés sont présentées au tableau 1. Le tableau 1.1 présente les conditions pour les périodes où les ventilateurs étaient éteints et, le tableau 1.2 présente les conditions avec les ventilateurs en marche. Pour le premier cas, le cas A, la température de l'air d'alimentation était de 8,8°C inférieure à la température de la pièce et, pour les deux autres cas, cas B et C, l'écart de température de soufflage était de 6,0 et 5,9°C respectivement (ventilateurs éteints). Les températures d'alimentation et les températures de l'air de la pièce n'ont pas varié par plus de 2°C durant les essais et les variations les plus importantes sont survenues pendant que les ventilateurs étaient en marche. Les vitesses moyenne de l'air au centre étaient les mêmes pour les trois cas durant les périodes avec ventilateurs fermés (0,07 m/s) et les vitesses de l'air étaient supérieures à 0,40 m/s avec les ventilateurs ouverts.

Les injections de CO_2 mesurées pour les trois cas sont montrées à la figure 4 et les valeurs des concentrations sont présentées au tableau 2. Comme le montre la figure 4, le profil des concentrations est semblable pour les trois cas avec des concentrations moyennes variant entre 1000 ppm et 1300 ppm pendant les périodes avec ventilateurs fermés et des valeurs inférieures à 600 ppm avec les ventilateurs en marche. La figure 5 présente un graphique des trois premières injections pour le cas A et permet d'observer plus en détail les variations des concentrations pendant la durée d'une injection. Au tableau 2, l'efficacité a été calculée avec la formule décrite dans la méthodologie et a été multipliée par un facteur de 100 pour obtenir des valeurs proches de l'unité. Pour les cas A, B et C, des valeurs respectives d'efficacité de 0,12, 0,15 et 0,20 ont été calculées pour la période avec ventilateur fermé et de 1,0, 1,2 et 1,4 avec ventilateur ouvert. La figure 6 montre la distribution des concentrations de CO_2 pour les trois cas pour toute la durée des essais. Pour cette figure, les concentrations sont classées en ordre décroissant et la concentration minimale de chacun des essais a été soustraite aux valeurs originales pour comparer les résultats sur une même base. Cette classification des données permet de comparer l'aire sous la courbe des concentrations.

Les résultats permettent de comparer la dilution mesurée pour les températures d'alimentation et de comparer les conditions de mélange entre les périodes où les ventilateurs sont ouverts ou fermés.

La distribution des concentrations de la figure 6 indique que les concentrations moyennes observées pour les trois cas ont varié avec la température d'alimentation. Si l'on utilise l'aire sous la courbe comme estimation relative de l'efficacité de dilution, le cas A, pour lequel la température d'alimentation est la plus basse serait classifié comme le pire cas, suivi du cas B et C qui ont une température d'alimentation semblable. La somme des concentrations sur la durée de l'expérience (incluant les périodes avec ventilateurs ouverts) donne un total de 2 x 10^5, 1,7 x 10^5, 1,3 x 10^5 ppm pour les cas A, B et C respectivement. Si on divise ces valeurs par les valeurs du pire cas, le cas A, la dilution observée pour le cas B serait 1,2 meilleure et 15,5 fois meilleure pour le cas C. En utilisant les valeurs d'efficacité calculées

Tableau 1. Températures et vitesses de l'air pour les cas étudiés.

Tableau 1.1. Ventilateurs de mélange éteints.

	TEMPÉRATURES (°C)					VITESSES (m/s)	
	ALIMENTATION		CENTRE DE LA PIÈCE			CENTRE DE LA PIÈCE	
CAS	Moyenne	Écart-type	Moyenne	Écart-type	Écart de soufflage	Moyenne	Écart-type
A	10.3	0.7	18.1	0.4	8.8	0.07	0.02
B	15.5	0.4	21.5	0.2	6.0	0.07	0.01
C	14.8	0.5	20.7	0.4	5.9	0.07	0.01

Tableau 1.2. Ventilateurs de mélange en marche.

	TEMPÉRATURES (°C)					VITESSES (m/s)	
	ALIMENTATION		CENTRE DE LA PIÈCE			CENTRE DE LA PIÈCE	
CAS	Moyenne	Écart-type	Moyenne	Écart-type	Écart de soufflage	Moyenne	Écart-type
A	11.3	0.0	20.1	0.4	8.8	0.45	0.03
B	15.6	0.7	22.3	0.2	6.7	0.42	0.02
C	15.3	0.4	21.6	0.4	6.3	0.42	0.02

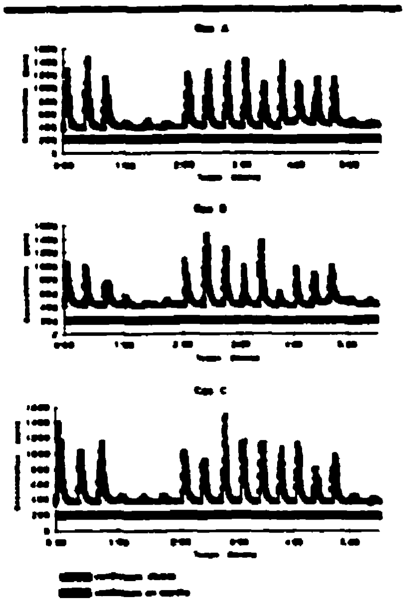

Figure 4. Concentrations de CO_2 pour les trois cas étudiés.

Tableau 2. Concentrations de CO_2.

Tableau 2.1. Ventilateurs de mélange éteints

	CONCENTRATIONS (ppm)				EFFICACITÉ DE DILUTION (ε X 100)			
CAS	Moyenne	Maximum	Minimum	Écart-type	Moyenne	Maximum	Minimum	Écart-type
A	1235	1441	1047	138	0.12	0.15	0.08	0.02
B	1077	1378	780	168	0.15	0.24	0.10	0.04
C	1026	1457	608	242	0.20	0.53	0.10	0.04

Tableau 2.2. Ventilateurs de mélange en marche.

	CONCENTRATIONS (ppm)				EFFICACITÉ DE DILUTION (ε X 100)			
CAS	Moyenne	Maximum	Minimum	Écart-type	Moyenne	Maximum	Minimum	Écart-type
A	471	496	449	18	1.02	1.27	0.79	0.2
B	439	448	417	14	1.20	1.58	1.06	0.2
C	498	543	485	32	1.42	2.11	0.79	0.5

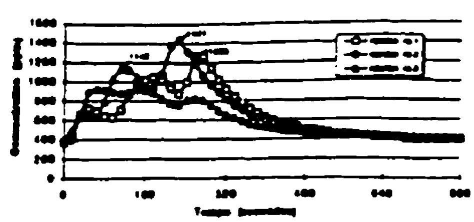

Figure 5. Trois premières injections, cas A (voir figure 4).

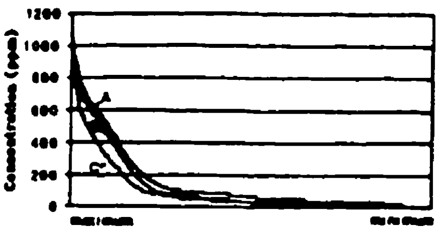

Figure 6. Aire sous les courbes de concentrations de la figure 4 (données classées en ordre décroissant).

par e, on obtient des ratios de 0,12, 0,15 et 0,20 pour les cas A, B et C respectivement. En divisant ces valeurs par celle du cas A, on obtient que la dilution observée est 1,3 fois meilleure pour le cas B et 1,7 fois meilleure pour le cas C. Ces valeurs sont plus élevées mais du même ordre que celles obtenues en faisant la somme des concentrations. Ainsi, l'équation de l'efficacité fournit une estimation semblable à la mesure de l'aire sous la courbe et peut être utilisée pour simplifier les calculs.

Les valeurs observées durant les périodes avec ventilateurs ouverts et ventilateurs fermés montrent la relation qui existe entre les vitesses de l'air et la dilution dans la pièce. Lorsque les ventilateurs fonctionnent, l'air de la pièce est dans une condition proche du mélange parfait et les vitesses de l'air sont en moyenne 6,1 fois plus élevées qu'avec les ventilateurs fermés. En comparaison, les concentrations maximales de CO_2 varient seulement dans un rapport de 2,4.

DISCUSSION

Les résultats présentés montrent l'effet de l'écart de température de soufflage et l'effet des ventilateurs sur l'efficacité. Ces deux aspects sont discutés ici séparément en comparant les résultats obtenus avec des méthodes de mesure d'efficacité globale. L'efficacité globale représente l'efficacité de la ventilation à distribuer de l'air dans l'ensemble d'un local et il existe une relation encore mal définie entre ces méthodes et les mesures de l'efficacité de dilution (*2*). Les comparaisons possibles doivent être faites en tenant compte du fait qu'une bonne distribution ne correspond pas nécessairement à une bonne dilution.

Pour les températures de soufflage, des mesures effectuées par Sandberg (*4*) ont montré des efficacités de ventilation globale de 50 et 60 % pour des différences de température de soufflage de 3°C et 6°C respectivement. Les résultats de Sandberg (*4*) sont pour l'ensemble d'une pièce et pour une configuration différente de la nôtre. Pour les cas décrits ici, les efficacités n'ont pas augmenté mais diminué avec une augmentation des écarts. On note cependant que les vitesses de l'air moyennes étaient semblables pour les trois cas malgré les différences de l'écart de température de soufflage.

Les conditions avec ventilateurs fermés et ouverts permettent de comparer le mélange actuel de la pièce avec un déplacement par piston. Selon les résultats de Sandberg (*4*), l'efficacité globale pour un déplacement par piston peut être dix fois plus élevée que pour un déplacement en court-circuit. Pour nos essais, l'efficacité de dilution a varié par un facteur de huit ce qui indique un mélange d'air entre le court-circuit et le déplacement par piston.

Comparativement à la méthode proposée par Fisk (*6*), la méthode utilisée ici permet de faire des mesures à un poste de travail sans avoir à injecter le gaz traceur dans l'ensemble d'un édifice. La méthode a aussi l'avantage de mettre dans une pièce un système qui simule l'activité humaine sans faire appel à des hypothèses sur les mécanismes de dilution ou de déplacement de l'air. Comme la méthode de Fisk (*6*) est seulement à l'étape de la formulation, il n'est pas encore possible de comparer les résultats.

CONCLUSIONS

Les résultats présentés ici permettent de conclure que la méthode proposée est sensible aux différences de conditions de mélange dans un local. La comparaison des résultats avec et sans ventilateurs a permis de déterminer que la méthode s'applique à une large gamme de vitesses de l'air pouvant être rencontrées sur le terrain. Pour les résultats des mesures avec différentes températures de soufflage, les résultats ne permettent pas encore de tirer des conclusions fermes et ces essais devront être répétés.

Un certain nombre de facteurs doivent être étudiés avant de pouvoir appliquer cette méthode sur le terrain. Pour les prochains essais, les débits d'air, plutôt que les températures d'alimentation seront variés pour pouvoir étudier l'effet des débits sur l'efficacité de dilution. Ceci permettra d'inclure ce paramètre dans la définition de l'efficacité. Aussi, dans un espace de bureau occupé, la méthode devra pouvoir tenir compte des changements de concentration durant la journée. Pour ce faire, des séries d'injection devront être effectuées avec des concentrations de fond différentes afin de normaliser les résultats. Si ces études sont concluantes, un appareil intégré pourrait facilement être développé. Comme la méthode est relativement simple et est automatisée, elle peut facilement être utilisée comme une technique de mesure standard. Éventuellement, une relation pourrait être établie entre les mesures d'efficacité et la perception des occupants par rapport à la dilution et à la distribution de l'air à leurs postes de travail.

REMERCIEMENTS

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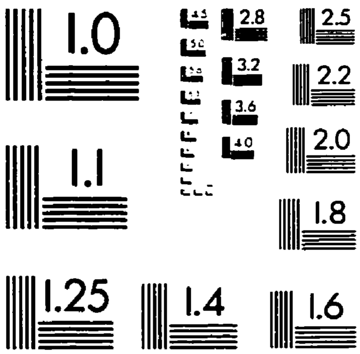
IMAGE EVALUATION TEST TARGET (QA-3)



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