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Impact of Combined Dilution and Pressurisation Effects of Ventilation Air on Indoor Contaminant Concentration

Key Words
Ventilation
Indoor air quality
Air pressurisation

Abstract
When outdoor air is the main source of pollutants indoors, mechanical air ventilation can be viewed as having two fronts of action in controlling indoor air quality. The first is its capacity to remove indoor air pollutants by dilution, and the second is its capability to prevent, through its pressurisation effect, the pollutant source (i.e. untreated outdoor air) from infiltrating, through the building envelope, to the occupied space. This paper discusses the impact of combined dilution and pressurisation potentials of ventilation air on indoor contaminant concentration when outdoor air is the main source of pollutants. Utilising an airflow model in conjunction with a one-compartment indoor air quality model, contaminant concentration behaviour within a single zone enclosure is predicted at various enclosure air leakage, system characteristics and pressurisation levels. Results from this study are indicative of the appreciable impact of the pressurisation effect of ventilation air which needs to be considered for a better assessment of ventilation air effectiveness and further enhancement of indoor air quality control.

Introduction

In urban and dusty environments, outdoor air can be a major source of pollutants and particulates which can contribute to the level of indoor contamination. Pollutants such as carbon monoxide, formaldehyde, suspended particulates and viable particles can be present at elevated concentrations in the ambient environment of urban areas [1]. These pollutants can be transported to the indoor space through air infiltration and ventilation systems. In both cases, the amount of transferred pollutant is determined by its concentration in the outdoor air and the volumetric flow rate of air delivered to the space [2]. This means that the reduction or even the elimination of air infiltration and the utilisation of air filtration techniques to clean the make-up air are the most effective and feasible approaches. Air infiltration through the exterior building envelope can be reduced by increasing the room air pressure which can be achieved by modifying the rate of supply and/or return air. A considerable amount of research has been carried out on airflow and air distribution, as well as air quality and contaminant behaviour, in buildings. The available knowledge clearly indicates the potential of ventilation air dual action in controlling indoor air quality and will be fundamental for the modelling approach in the current study.

Models for predicting indoor air quality (IAQ) ranging from a simple one-compartment to a more comprehen-

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sive multi-compartment one have been developed [1, 3, 4]. In all cases, the contaminant mass balance is performed separately for each zone (i.e. compartment) and airflow rates across various paths connecting the indoor and outdoor environments are required. Experimental and theoretical models for predicting airflow in buildings under natural and/or mechanical driving potentials have been developed for a wide range of building types and applications [5–12]. A major experimental effort has recently been carried out as part of the EC PASCOOL research project [13] to investigate natural ventilation phenomena. Although experimental models reveal more knowledge and improve experience, theoretical models tend to be more flexible and more practical in predicting airflow rates. Depending on the complexity of the airflow process, a simplified theoretical model or a multi-zone airflow network model can be used to predict airflow rates across different building elements. In multi-zone models, however, airflow rates across interconnecting airflow elements are additionally required. Models for predicting simultaneous airflow through the building exterior envelope and interspace airflow elements, both under thermal and wind forces [14, 15], and supporting wind pressure data [16], have been developed. By utilising these concepts, indoor air humidity behaviour within single-zone and multi-zone enclosures has been investigated [17, 18].

The main purpose of air ventilation is to remove, by the process of dilution, indoor generated pollutants, provide air circulation within the space and maintain a normal concentration of respiratory gases in order to maintain an acceptable indoor environment in terms of air quality and thermal comfort. When of acceptable quality, the outdoor air can be directly utilised in controlling IAQ, otherwise, mechanical ventilation, through which the outside air is treated, becomes the primary practical option. In some cases, however, both natural and mechanical driving potentials can be active in inducing air ventilation. Regardless of the type of ventilation, the right quantity of air of the right quality has to be delivered to the space to satisfy its thermal and air quality requirements. The overall efficiency of the ventilation process, nevertheless, is not only determined by the quantity and the quality of the ventilation air, but additionally by its effectiveness. Many definitions of ventilation effectiveness are available in the literature [4, 11, 19, 20] but all describe the degree of mixing between room air and ventilation air. Efforts have been made to differentiate between air change efficiency, which describes the efficiency at which the room air is replaced by fresh air, and ventilation effectiveness, which measures how quickly an air-borne contaminant is removed from the room [3 21]. Mathematically, ventilation effectiveness can be expressed as the ratio between the concentration of contaminants in the exhaust air and the average concentration of the contaminants in the room at a steady state [3]. Experimental procedures for evaluating ventilation effectiveness using the tracer decay technique have been suggested [22, 23]. When the space is pressurised by ventilation air and outdoor air is the main source of the contaminant under consideration, the definition of ventilation effectiveness should be modified to include the effect of ventilation air diluting capacity as well as its effect in preventing the contaminant from getting into the space. Pressurisation performance and impact on contaminant dispersion, and transfer into the space, have been the subject of several recent studies [24–26]. Results from these studies have indicated the potential ability of the pressurisation technique in preventing the flow of outside contaminants and have shown the importance of building physical parameters and supply airflow rate on the performance of the technique. The effects of equipment size, control strategies and HVAC system configurations on building pressurisation have also been studied [25].

In spite of the potentially positive effect of ventilation air pressurisation on the IAQ when outdoor air is the main source of contamination, it is not evident that this subject has received sufficient attention in the literature where ventilation air is mainly viewed as a diluting medium. The objective of this paper is to investigate theoretically the combined diluting and pressurisation effects of mechanical ventilation air in controlling air quality. In order to achieve this objective, the behaviour of contaminant concentration needs to be evaluated and compared under different enclosure air leakage characteristics, filtration system efficiencies and pressurisation levels. Results from this study are expected to increase knowledge about ventilation air dual-potential in IAQ control and enhance understanding of the combined impact of natural and mechanical air transport potentials in IAQ.

Methods

Modelling Approach

A one-compartment IAQ model was used in conjunction with a single-cell airflow model. The one-compartment model was thought to be appropriate and it clearly and fully addressed the main objective of the study. Airflow rates predicted by the air flow model were used as an input to the IAQ model. Variations in contaminant concentration within an enclosure at different air leakage characteristics, filtration system efficiencies and air pressurisation levels were evaluated.

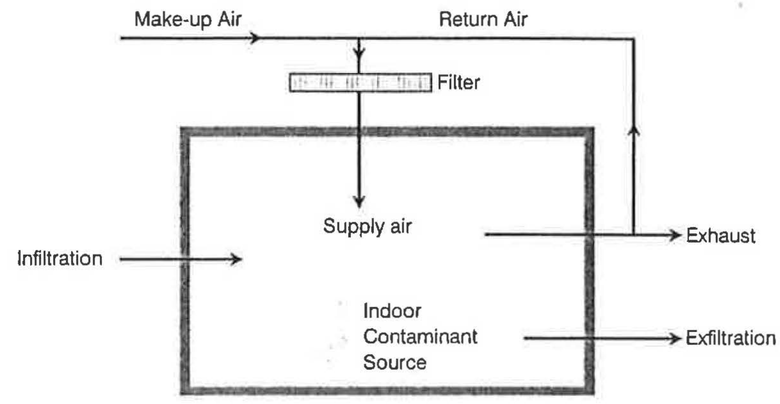

Fig. 1. A schematic of the IAQ model.

The IAQ Model. Variations of pollutant concentration within the space were estimated using the IAQ model with a schematic as shown in figure 1. The model accounts for the contribution from infiltrating air, exfiltrating air, mechanically supplied air, indoor pollutant generation and the filtration process. The model also accounts for variable mixing between the recirculated and the make-up air which is prompted by the variability of the difference between the supply air and return air rates that is necessary to achieve the required pressurisation levels. Air filtration is an integral part of any ventilation process, but it is of special importance to the issue being addressed in this study: a means of bringing the outdoor air (which is assumed to be a major source of pollutants) to an acceptable quality before being introduced for ventilation or pressurisation. The filtration process, however, has been treated in a simplified manner by assuming constant filtration efficiency independent of airflow rate and contaminant characteristics. This assumption is justified since no specific contaminant is considered, and to obtain a focused picture of the ventilation air pressurisation impact on contaminant concentration. In order to describe mathematically the model, it was also assumed that the contaminant and the indoor air were perfectly mixed and there was no adsorption or desorption by interior materials. This assumption is justifiable for the purpose of the present study since spatial contaminant distribution was not required and the impact of the absorption and desorption process would not jeopardise the validity of the approach intended to evaluate the impact of the interaction of infiltration and building pressurisation on IAQ. Based on the above assumptions and utilising contaminant mass balance, the rate of change in contaminant concentration (for abbreviations, see the appendix) can be given by:

$$V_r \frac{dc_i}{dt} =$$

$$Q_{inf} c_o - Q_{exf} c_i + Q_s(1 - \varepsilon_f)(\alpha_o c_o + \alpha_r c_i) - (Q_s - \delta Q_m)c_i + N. \quad (1)$$

Solving equation 1 yields:

$$c_i(t) = (c_i^o - \beta/\alpha)\cdot \exp(-\alpha t) + \beta/\alpha \quad (2)$$

where

$$\beta = [Q_{inf} c_o + Q_s(1 - \varepsilon_f)\cdot \alpha_o c_o + N]/V_r$$

and

$$\alpha = [Q_{exf} - (1 - \varepsilon_f)\cdot \alpha_r Q_s + Q_s - \delta Q_m]/V_r.$$

Under steady-state conditions, contaminant concentration can be given by:

$$c_i,ss =$$

$$[(Q_{inf} + Q_s(1 - \varepsilon_f)\alpha_o)c_o + N]/[Q_{exf} - (1 - \varepsilon_f)\alpha_r Q_s + (Q_s - \delta Q_m)]. \quad (3)$$

From equation 3 it is clear that, under steady-state conditions, the contaminant concentration is independent of the room volume, yet it is an important parameter in determining the time constant of the process. When no mechanically supplied air is provided to the space, contaminant mass balance is given by:

$$V_r \frac{dc_i}{dt} = Q_{inf} c_o - Q_{exf} c_i + N. \quad (4)$$

By solving equation 4, contaminant concentration under natural airflow potential can be expressed by:

$$c_i(t) = \left(c_i^o \frac{Q_{inf} c_o + N}{Q_{exf}}\right)\cdot \exp\left(\frac{-Q_{exf}}{V_r} t\right) + \frac{Q_{inf} c_o + N}{Q_{exf}} \quad (5)$$

and, under steady-state conditions, it is given by:

$$c_i,ss = (Q_{inf} c_o + N)/Q_{exf}. \quad (6)$$

If indoor temperature is equal to outdoor temperature (i.e., $Q_{inf} = Q_{exf} = Q_a$), steady state contaminant concentration is reduced to:

$$c_i,ss = c_o + \frac{N}{Q_a}. \quad (7)$$

Examination of equation 6 shows that, in the absence of the indoor pollutant source, contaminant concentration is not only determined by the outdoor concentration, but also by the ratio between the exfiltrating and infiltrating air volumetric flow rate. This means that the indoor concentration level is expected to be higher than the outdoor concentration at higher outdoor temperatures, and vice versa. At equal indoor and outdoor temperatures, the steady

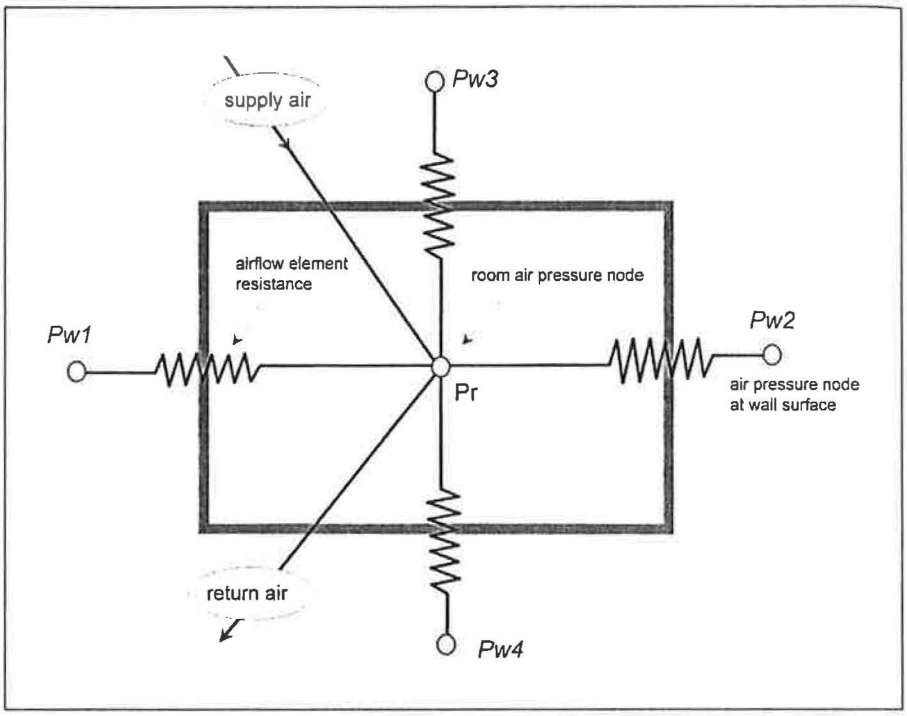

Fig. 2. A schematic of the airflow model. Pr = Room air pressure node.

state indoor concentration will be equal to the outdoor level in the absence of indoor sources, as indicated by equation 7.

The Airflow Model. Evaluation of air infiltration and exfiltration rates under a variable driving potential (i.e. wind velocity) is an essential component for solving equation 2. To achieve this, a single-zone airflow network model shown in figure 2 was utilised. The model describes a rectangular enclosure with four leaking walls under different pressure differentials determined mainly by wind velocity and enclosure physical characteristics. Wind induced pressure on an exterior enclosure surface is determined by the wind velocity V and the wind pressure coefficient C_p, according to equation 8.

$$P_w = C_p \rho_{ao} V^2/_2. \tag{8}$$

Values of wind pressure coefficients can be negative or positive and vary according to wind direction and enclosure geometry.

Airflow due to the stack effect was assumed to be negligible, considering the relatively small pressure differential induced by thermal forces over the height of the single-zone enclosure compared to that produced by wind. Furthermore, the supply and return airflow rates were assumed to be mechanically controlled by the ventilation system and hence independent of the air pressure within the space. These assumptions were made to better demonstrate the results and the approach to the problem being considered.

By employing the air mass balance concept and numerically solving the resulting non-linear algebraic equation, the space air pressure could be evaluated at different boundary conditions and pressurisation levels. The air mass balance can be mathematically described by:

$$\sum_{j=1}^{n} m_j = 0, \tag{9}$$

where n indicates the number of airflow paths crossing the space boundaries. The airflow rate across each air path can be generally related to the pressure differential across it through the power law given by equation 10:

$$m = \rho_a K A_w (\Delta P)^n. \tag{10}$$

Based on equation 10, the resulting air mass balance equation takes the following form:

$$\sum_{j=1}^{FI} \rho_{ao} A_{w_j} K_j (\Delta P)_j^n - \sum_{j=1}^{FO} \rho_{ai} A_{w_j} K_j (\Delta P)_j^n + \rho_{as} Q_s - \rho_{ai}(Q_s - \delta Q_m) = 0, \tag{11}$$

where FI and FO represent air inflow and air outflow paths, respectively. The values of the flow component n can range from 0.5 for turbulent orifice flow to 1.0 for laminar flow associated with very fine airflow paths. In reality, both airflow types are found in buildings, hence a flow exponent of between 0.5 and 1.0 can be expected. Results from experimental studies showed that a value of 0.65 would fairly represent the actual flow in buildings. In this study, a flow exponent value of 0.65 was used for predicting the air leakage rates through exterior walls.

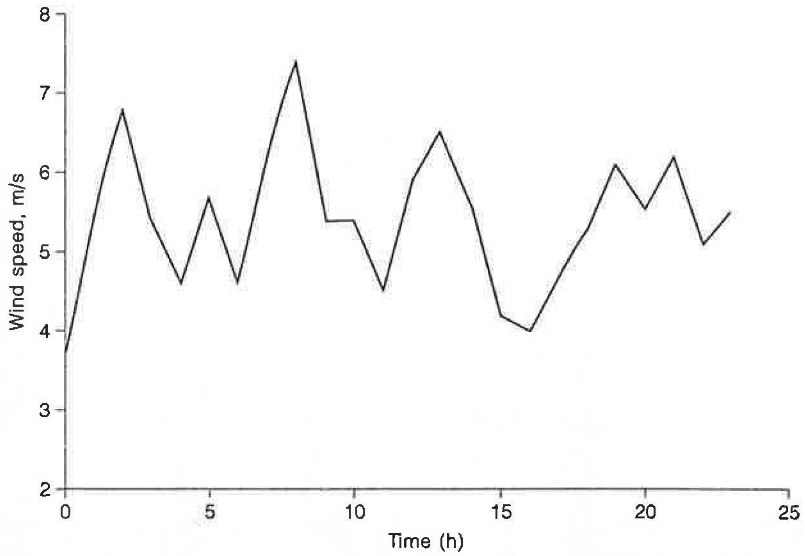

Fig. 3. Average hourly wind speed during simulation period.

Application and Discussions

Both the airflow and the IAQ models utilised in this study are formulated based on well-established theories and concepts (e.g. mass balance). Predictions of both models have been numerically verified by checking both air and contaminant mass balances. Wind pressures required for the airflow model are evaluated based on average pressure coefficients given by Swami and Chandra [16] as a function of incident angle and building side ratio. These pressure coefficients were found to be quite accurate in predicting natural ventilation airflow rates. These models were used to investigate the impact of combined pressurisation and dilution effects of ventilation air on pollutant concentration behaviour within a 600 m^3 (20 × 10 × 3 m) single-zone enclosure. The hourly variations of pollutant concentration were predicted under varying wind speed as shown in figure 3. The wind direction, however, was assumed to remain perpendicular to the short side of the enclosure. The corresponding airflow rates across the different walls were calculated based on equation 10, and the pressure differential across each wall was evaluated using the airflow network modelling technique described earlier. The return air at 21 °C was mixed with the make-up air at 41 °C before being cooled down to 15 °C. The mixture passed through a filter with a removal efficiency of 50%. The amount of the make-up air varied according to the required pressurisation level, but it was not less than 20% of the total supply air volumetric flow rate. The outdoor air was assumed to be the main source of pollutant with a concentration of $0.001 \cdot 10^{-6}$ $g \cdot m^{-3}$.

In the absence of air pressurisation, the pressure differential across the exterior walls, and consequently the air infiltration rates, are determined by the wind forces. The impact of ventilation air on hourly contaminant concentration in the absence of pressurisation for an average airtightness enclosure ($C_w = 1.0 \cdot 10^{-4}$ $m^3 \cdot m^{-2} \cdot Pa^{0.65} \cdot s$) is shown in figure 4. It can be seen that when no ventilation is employed, contaminant concentration exhibits an exponential increase with no major impact of wind velocity fluctuations on the general behaviour of the contaminant concentration curve. Introducing ventilating air at a rate of 0.25 $m^3 \cdot s^{-1}$ with a system filtration efficiency of 50% substantially reduces contaminant concentration to a level close to 20% of that obtained in the absence of ventilation as shown in figure 4. The reduction in contaminant concentration is partly due to the loss via the exhausted part of the return air but is mainly due to the filtration process. This level can be further decreased by reducing the air infiltration rate by raising space air pressure. Figure 5 illustrates hourly contaminant concentration, for different enclosure airtightness levels, when space air pressure was raised by a net volumetric airflow rate of 0.04 $m^3 \cdot s^{-1}$ (about 0.05425 $kg \cdot s^{-1}$) resulting from supplying air at a rate of 0.25 $m^3 \cdot s^{-1}$ and returning it at 0.21 $m^3 \cdot s^{-1}$. For the untight enclosure, contaminant con-

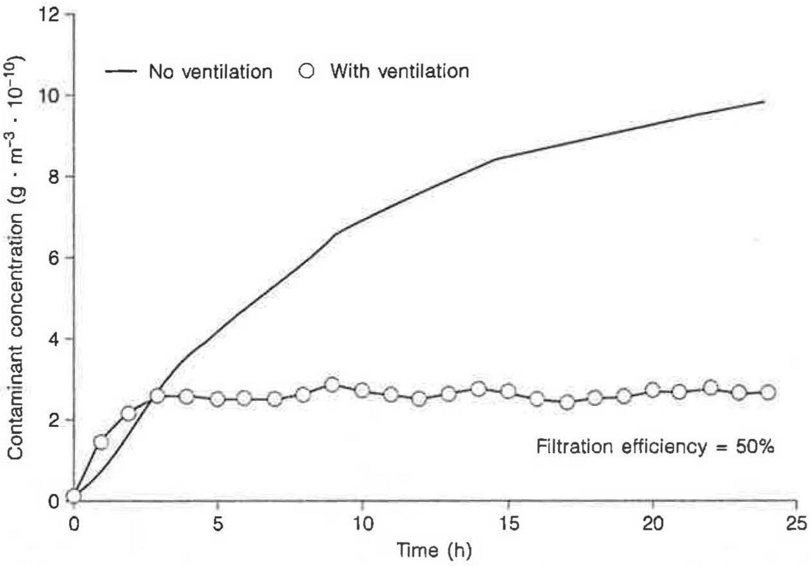

Fig. 4. Average of ventilation air impact on contaminant concentration within an enclosure at average air tightness level.

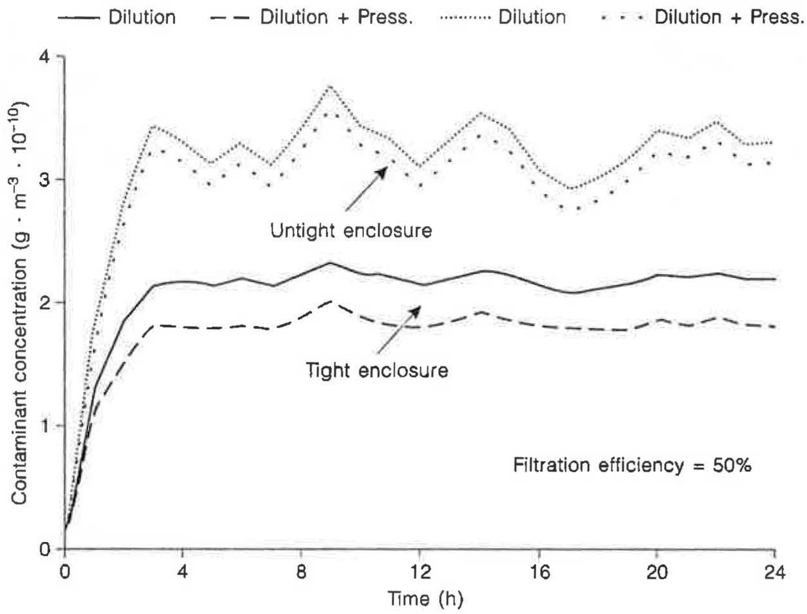

Fig. 5. Impact of air pressurization on indoor contaminant concentration for different enclosure airtightness levels.

centration was much higher and more responsive to fluctuation in wind velocity. The impact of air pressurisation is evident for both enclosure airtightness levels but more pronounced for the airtight enclosure with an average reduction of about 15% in contaminant concentration. This is due to the fact that the air infiltration rate is more sensitive to pressure difference across the envelope with increased enclosure airtightness. Figure 6 shows the effect of pressurisation on average contaminant concentration at different enclosure air leakage levels. The maximum decrease in contaminant concentration corresponds to a wall air leakage coefficient of about $0.5 \cdot 10^{-4}\ m^3 \cdot m^{-2} \cdot Pa^{0.65} \cdot s$. Increasing the air leakage coefficient above this level resulted in a higher contamination level due to a

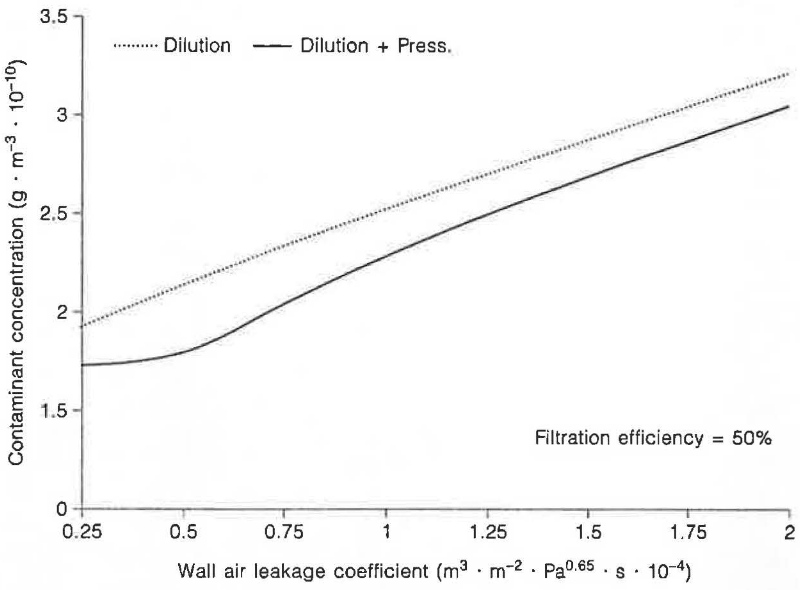

Fig. 6. Impact of enclosure air leakage characteristics on contaminant concentration under dilution and combined dilution and pressurisation effects.

decreased pressurisation level and consequently an increased infiltration rate. This indicates that increasing the air pressurisation rate will be beneficial in reducing contaminant concentration. Decreasing the air leakage coefficient, on the other hand, requires a lower pressurisation air rate than that provided in order to eliminate the resulting air infiltration. Hence, at elevated pressurisation air rates, unwanted contaminant components can be introduced through the ventilation air, making its pressurisation effect less beneficial and possibly harmful.

In general, the degree of influence of air pressurisation is determined by the level of contribution of the air infiltration process to contaminant mass balance, and to a great extent by the effectiveness of the filtration process. Figure 7 illustrates the level of reduction in contaminant concentration within an airtight enclosure at different filtration efficiencies. Since the filtration process is the only working removal mechanism when outdoor air is the source of contaminant, the concentration level of contaminant will be greatly influenced by system filtration efficiency. Increasing the filtration efficiency from 50 to 80% reduces contaminant concentration by more than 50%. Furthermore, the impact of space pressurisation in reducing contaminant concentration was substantially enhanced by increasing filtration efficiency. At 50% filtration efficiency, contaminant concentration was reduced by 15% when space pressurisation was used. Under the same level of pressurisation, contaminant concentration was reduced by 35% when filtration efficiency was increased to 80%. Higher filtration efficiency will always lead to increased dilution capacity and an enhanced pressurisation effect of the ventilation air. Figure 8 shows that the average contaminant concentration (evaluated over a 24-hour period) is substantially reduced as filtration efficiency increases. This effect is more pronounced as the filtration efficiency is increased above zero and gradually diminishes as filtration efficiency increases. For the modelled enclosure, increasing filtration efficiency from zero to 10% has the same effect on reducing contaminant concentration as increasing it from 30 to 80%. Therefore, it is always important to relate the cost of increasing filtration system efficiency to the increased benefits pertaining to IAQ. The effect of air pressurisation in reducing the contaminant level at various filtration efficiency levels above zero is shown to be almost the same in absolute terms but substantially increases, percentage-wise, with filtration efficiency. When no filtration is employed, space pressurisation will have a limited short-term impact on reducing contaminant concentration, which completely diminishes under steady-state conditions.

In order to obtain the maximum benefit from space pressurisation in reducing contaminant concentration, the level of pressurisation must be enough to eliminate air infiltration but not so as to introduce an unwanted contaminant source. Figure 9 illustrates the impact of air pressurisation rate on contaminant concentration behav-

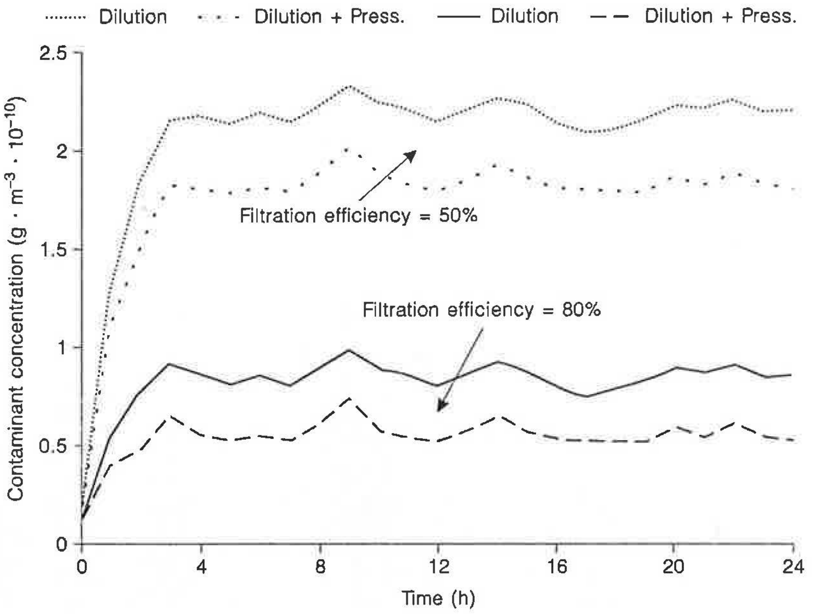

Fig. 7. Contaminant concentration within an airtight enclosure at different filtration efficiencies.

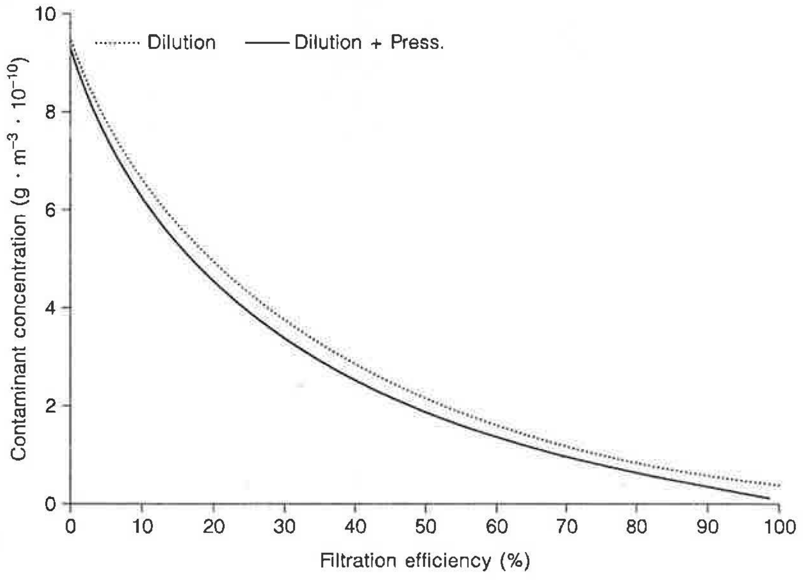

Fig. 8. Impact of filtration efficiency on contaminant concentration within an airtight enclosure under dilution and combined dilution and pressurisation effects.

iour within an airtight enclosure. The provision of a pressurisation rate of 0.04 $m^3 \cdot s^{-1}$ results in a reduced contaminant concentration below the dilution determined level, while increasing it to 0.08 $m^3 \cdot s^{-1}$ marginalises the contribution of the air infiltration process and substantially increases the contaminant concentration above the dilution level. This can be further recognised from figure 10 which shows variations in average contaminant concentration with the pressurisation air rate for different enclosure airtightness levels. At low pressurisation air rates, the difference in contaminant concentration between the different enclosures is mainly due to the difference in air infiltration rates. The impact of air pressurisation becomes more noticeable as the pressurisation air rate

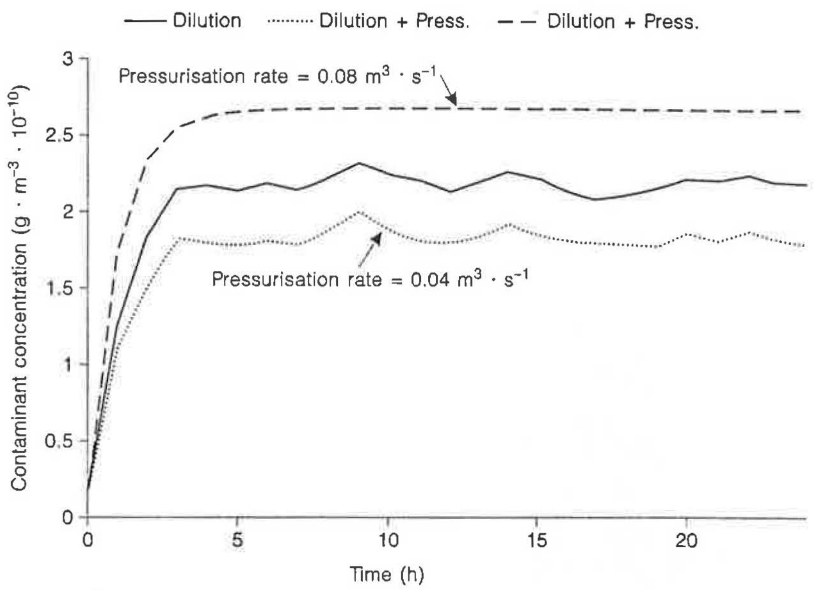

Fig. 9. Impact of air pressurisation level on contaminant concentration within an airtight enclosure.

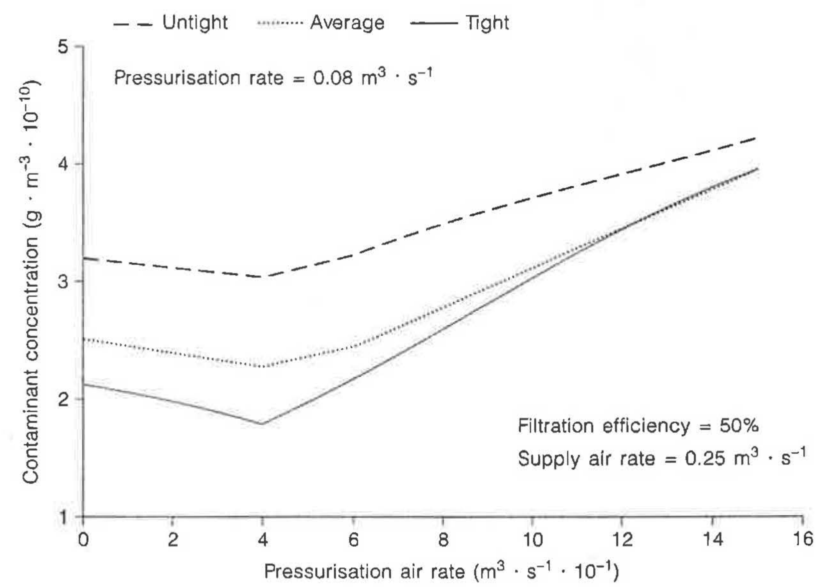

Fig. 10. Impact of air pressurisation level on contaminant concentration for different enclosure airtightness levels.

increases, with the maximum effect obtained at a pressurisation rate of about 0.04 $m^3 \cdot s^{-1}$. Below this air pressurisation rate, the average contaminant concentration at all enclosure airtightness levels is inversely related to the pressurisation level. Increasing the pressurisation air rate further results in increased contaminant concentration, indicating a diminishing role of air infiltration and the dominance of ventilation air, which is evident at a high pressurisation air rate when contaminant concentration becomes independent of the airtightness level. Although the same behaviour is experienced at all enclosure airtightness levels as pressurisation is increased, the airtight enclosure exhibits a more sensitive response as indicated by the slope of the corresponding concentration curve.

Conclusions

An airflow model has been used in conjunction with an IAQ model to investigate contaminant concentration in a single zone enclosure under combined dilution and pressurisation effects of ventilation air, when outdoor air is the main source of contaminant. The airflow model predicts airflow rates under wind forces, but assumes negligible thermal forces. For the application presented in this study, thermal forces can be safely neglected due to enclosure characteristics and the dominance of wind forces during the simulation period. In general, however, thermal forces (i.e. stack effect) need to be accounted for when estimating air flow rates. The airflow model takes into account all relevant processes determining contaminant concentration but assumes a non-active absorption/desorption process and a filtration process independent of contaminant characteristics and airflow rate.

The behaviour of contaminant concentrations within the single-zone enclosure has been evaluated for different enclosure air leakage characteristics and ventilation system filtration efficiencies. The peak reduction in contaminant concentration occurs at the point of equalisation between indoor and positive outdoor pressures, provided that the differential air mass needed to reach the equalisation point results in less contaminant mass than the eliminated air infiltration process. Increasing space air pressure above the equalisation level will certainly result in a net increase in contaminant concentration. Different enclosure airtightness levels require different differential air masses (i.e. pressurisation air rates) to achieve the same level of pressurisation and offer different contaminant concentration reduction potentials by space air pressurisation. Higher filtration efficiency is associated with an enhanced dilution capacity of the ventilation air and hence an increased effectiveness of space pressurisation. The effectiveness of ventilation air, however, is more sensitive to the filtration process at low filtration efficiency levels. When no filtration is employed, both the dilution and pressurisation effects of ventilation air will be completely inactive in reducing contaminant concentrations.

Results from this study are indicative of the appreciable impact of ventilation air pressurisation on reducing contaminant concentrations when outdoor air is a major contaminant source. In this situation, ventilation air pressurisation should be viewed as a potentially practical and effective means of controlling IAQ, considering the fact that elimination of the contaminant source (i.e. infiltrating outdoor air) is always better than diluting it after infiltrating into the space. Additionally, it can be concluded that a more realistic and comprehensive definition of ventilation air effectiveness, different from the current one, is needed to account for the ventilation air pressurisation effect. Finally, it must be noted that the modelling approach in this study is based on several assumptions and results are based on a hypothetical case study in which a hypothetical enclosure and contaminant are modelled. Future studies should investigate the dual impact of ventilation air on contaminant concentration within real buildings and for specific contaminants, and more sophisticated airflow and air quality models should be utilised to account for absorption/desorption by interior materials, together with a more comprehensive consideration of the parameters influencing air infiltration rates and supply air flow rates under different space pressures. Of further importance is the incorporation of a more representative air filtration model specifically designed to suit the particular contaminant under consideration.

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Appendix: Nomenclature

A_w = Wall area, m^2
c_i = Indoor contaminant concentration, $g \cdot m^{-3}$
c_o = Outdoor contaminant concentration, $g \cdot m^{-3}$
c_i^o = Initial contaminant concentration, $g \cdot m^{-3}$
C_p = Wind pressure coefficient
K = Exterior wall air leakage coefficient, $m^3 \cdot m^{-2} \cdot Pa^{0.65} \cdot s$
$m^{\cdot}$ = Mass flow rate, $kg \cdot s^{-1}$
N = Contaminant generation rate, $g \cdot s^{-1}$
n = Flow exponent
P_w = Wind pressure, Pa
Q_s = Supply air volumetric rate, $m^3 \cdot s^{-1}$
Q_{exf} = Exfiltrating air volumetric rate, $m^3 \cdot s^{-1}$
Q_{inf} = Infiltrating air volumetric rate, $m^3 \cdot s^{-1}$
Q_a = Airflow rate, $m^3 \cdot s^{-1}$
V_r = space volume, m^3
V = wind velocity, $m \cdot s^{-1}$
t = Time, s
ε_f = Filtration efficiency
α_o = Volumetric flow rate ratio between outdoor air and supply air
α_r = Volumetric flow rate ratio between return air and supply air
δQ_m = Pressurisation airflow rate, $m^3 \cdot s^{-1}$
ΔP = Air pressure differential across airflow element, Pa
ρ_a = Air density, $kg \cdot m^{-3}$
ρ_{as} = Supply air density, $kg \cdot m^{-3}$
ρ_{ao} = Outdoor air density, $kg \cdot m^{-3}$
ρ_{ai} = Indoor air density, $kg \cdot m^{-3}$

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