Indoor Air V1 5

1643

EFFECT OF REDUCED BUILDING VENTILATION RATES ON OCCUPANT EXPOSURE AND RESPONSE TO CARBON MONOXIDE

William E. Lambert and Steven D. Colome
Program in Social Ecology, University of California, Irvine, U.S.A.

Abstract

In the weatherization of building structures to minimize convective heat loss, the air exchange rate is reduced. Pollutants of indoor origin are retained near the occupants. Further, outdoor pollutants may be concentrated indoors under particular peak and duration conditions. The health significance of this latter capacitance effect was evaluated with a generalized indoor-outdoor model for a conservative pollutant. Protection against transient outdoor peaks was found to vary as a function of exchange rate, ambient peak height, duration and periodicity. Under conditions approaching steady state, indoor fluctuation is dampened and geometric mean concentrations increase as exchange rates are reduced. Using a predictive equation for carboxyhemoglobin formation, a reference individual's response to indoor versus ambient profiles was calculated. The traditional assumption that reduced ventilation rates are protective against outdoor peaks was evaluated in the context of a generally reduced variance about the mean in indoor profiles.

Introduction

Energy conservation measures are often directed at sealing, or "weatherizing", building structure to prevent heat losses through joints and cracks. Tightening a structure reduces the air exchange rate of the interior with the outside, effectively retaining the indoor parcels of air, preventing their exfiltration. More slowly escaping pollutants that are generated from indoor sources are retained near occupants.

While exposure of building occupants to pollutants generated indoors is important, it is not the primary focus of this research. Rather, we examine the effect of decreased air exchange on indoor pollutants originating from outdoor sources. It is widely recognized that decreased air exchange rates protect building occupants from exposure to short-term high outdoor exposures. However it is much less commonly appreciated that decreasing the air exchange rate may, under particular peak and duration conditions, concentrate outdoor pollutants indoors. Over the longer term, a tightly sealed structure may effectively act as a capacitor of outdoor pollutant fluxes. The health significance of this phenomena for building occupants is that pollutant exposure levels and duration may be increased over those experienced outdoors.

It is the objective of this modeling effort to characterize the indoor response to constant and fluctuating outdoor pollution levels. In turn, the total exposure and biologic response of building occupants will be related to outdoor profile conditions and air exchange rates.

Methods

Historically, simulation modeling of indoor air pollution has utilized the basic mass balance concept in which first order linear kinetics are used to describe pollutant flux (1, 3, 4, 5, 6, 7). This general equation may be pared to fit the modeling situation of interest: analysis of the effect of outdoor pollution levels on the indoor environment. Therefore, indoor source terms and the recirculating loop function are dropped from Ishizu's formulation to yield:

$$V dc = C_o Q_i dt - C_i Q_i dt \qquad (1)$$

where $V \equiv$ volume of the room
$t \equiv$ time
$C_o \equiv$ concentration of the pollutant in the outdoor air
$Q_i \equiv$ volume rate of intake of outdoor air
$C_i \equiv$ concentration of pollutant in the room

Rewriting (1):

$$\frac{dC_i}{dt} = \frac{Q_i}{V}(C_o - C_i) \qquad (2)$$

Since $\frac{Q_i}{V}$ equals the air exchange rate a, substituting in (2) yields:

$$\frac{dC_i}{dt} = a(C_o - C_i) \qquad (3)$$

Equation (4) is the basic algorithm used in the computer simulation predicting indoor response to periodically fluctuating outdoor pollutant conditions. Hypothetical outdoor profiles were utilized to analyze the effects of peak concentration and periodicity on indoor response. In addition, 24-hour sequences of hourly carbon monoxide averages from California Air Resources Board data, were used to analyze the indoor response to more complicated outdoor pollutant patterns typical of real life conditions.

Comparisons of pollutant concentration-time curves were performed via calculation of the arithmetic mean and standard deviation, geometric mean and standard deviation, and numerical integration.

Carboxyhemoglobin (COHb) formation was predicted via the Coburn-Forster-Kane (2) equation. These calculations were performed on end-minute values of concentrations.

Results and Discussion

Theoretical. Integrating (3):

$$C_i = C_i e^{-at} + C_o(1 - e^{-at}) \qquad (4)$$

it is revealed that the indoor concentration is determined by the "decay rate" of the pollutant present indoors and the "infiltration rate" from outdoors to indoors.

Figure 1 illustrates the indoor buildup of pollutant as predicted by equation (3) under conditions of constant outdoor concentration. This figure and the previously described relationships provide the basis for predicting the lag time for reaching the "maximum" indoor concentration under a particular outdoor profile. From equation (4) and assuming $C_o > C_i$ at all dt, then:

$$C_i = C_o(1 - e^{-at}) \qquad (5)$$

In light of the asymptotic nature of the relationship, it is necessary to define the lag time as the time taken to reach 99% of the $C_{i\ max}$.

It follows that,

$$C_i / C_{i\ max} = 0.99$$

$$0.99 = 1 - e^{-at}$$

and

$$t_{lag} = \frac{4.60}{a} \qquad (6)$$

Thus, the lag time (t_{lag}) may be calculated for any given air exchange rate a (Figure 2). It is important to note that periodicity has no effect on the time lag which is exclusively determined by the air exchange rate a. Conversely, $C_{i\ max}$ is determined by air exchange rate and periodicity. Calculation of $C_{i\ max}$ for a system condition of multiple outdoor peaks requires a consideration of superpositioning of the outdoor pulses.

Analysis of the components of the ventilation process during a multiple outdoor peak regime is presented in Figure 3. It is assumed that the decay or exfiltration of pollutants from each outdoor peak is independent. The sequence of outdoor pulses develops a compound set of exponentially decaying "tails". Since outdoor pollutant input over time is regular, it is the rate of exfiltration which structures the indoor profile. Indoor sources would be additive upon this outdoor baseline and influence the indoor environment as a function of the exfiltration rate.

At steady state, levels of protection as measured by indoor maxima, increase exponentially as air exchange rates are decreased (Figure 4).

Substantial levels of protection, greater than 30%, are afforded at reduced ventilation rates typical of weatherized structures (i.e., at less than 1 ach). At higher air exchange rates (i.e., greater than 1 ach) protection does not continue to increase with decreasing frequency.

Application to Observed Outdoor Profiles. Application of the model to actual outdoor measurements of carbon monoxide (CO) allows comparison of indoor predicted levels versus those outdoors. Simulation runs were performed for several different types of outdoor CO profiles. One profile typical of a commuting area is presented to illustrate the mediating effect of a structure on exposure to outdoor sources (Figure 5). The modeling runs covered the range of well-ventilated (2 ach) to tightly sealed (.1 ach) conditions. Each run was allowed to continue to steady state conditions before calculation of distributions (Figure 6) and biological response (Figure 7).

Simulations indicate that decreased air exchange rates do protect occupants from peak exposures. Relative to outdoors, indoor peaks are dampened and lag behind. When outdoor peaks are of sustained duration and/or separated by short time periods, structures must be very tight (ach $\leq$ 0.25) to be "protective". Further, under the extreme conditions of sustained high outdoor concentrations a structure must approach 0.1 ach to be protective.

Generally, other indoor-outdoor pollutant models have only looked at short-term indoor environment response, and have therefore not been sensitive to the observation that the geometric mean indoor level increases slightly as air exchange rates decrease (Figure 6). In terms of health significance, the biological response of building occupants to fluctuating pollutant levels may not only be dependent on the absolute concentration or mean level, but also the time course of the exposure.

For the CO model, the response (carboxyhemoglobin formation) for a reference individual was used to compare outdoor versus indoor exposures (Figure 7). As air exchange rates decrease, the geometric mean of COHb increases a small amount while the variance about the mean greatly decreases. However, a counterintuitive finding is that under conditions of sustained outdoor peaks (e.g., conditions approaching or exceeding air quality standard levels) a tight building will aggravate indoor exposure to a conservative pullutant to a small degree. However, a counterintuitive finding is that under conditions of sustained or repeated outdoor peaks (e.g., conditions approaching or exceeding air quality standard levels) a tight building will aggravate indoor exposure to a conservative pollutant to a small degree. Any resulting health effects will depend on the relative importance of average or peak exposures.

References

(1) Birenzvige, A. A model to calculate the indoor concentration of a chemical contaminant. 76th Annual Meeting of the Air Pollution Control Association 1983; 64.7.

(2) Coburn, R.F., Forster, R.E., & Kane, P.B. Considerations of the physiology and variables that determine blood carboxyhemoglobin concentration in man. J. Clin. Invest. 1965; 44:1899-1910.

(3) Ishizu, Y. General equation for the estimation of indoor pollution. Envir. Sci. Technol. 1980; 14:1255-7.

(4) Lorenz, F. Calculation of the ventilation requirements in the case of intermittent pollution: Application to enclosed parking garages. Environ. Int. 1982; 8:515-24.

(5) Shair, F.H., Heitner, K.L. Theoretical model for relating indoor pollutant concentrations to those outside. Environ. Sci. Technol. 1974; 8:444-51.

(6) Silberstein, S. Outdoor sources of indoor air pollution. Energy and Buildings 1979; 2:55-64.

(7) Turk, A. Measurement of odorous vapors in test chambers: Theoretical. ASHRAE 1963; 9:55-8.

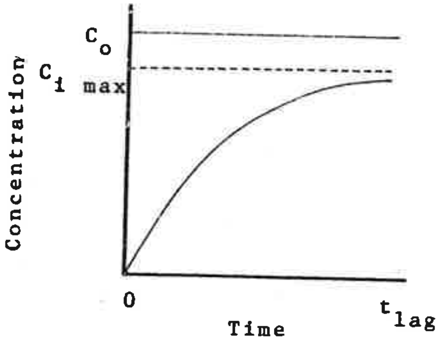

Fig. 1. Idealized representation of indoor pollutant buildup as driven by constant outdoor pollutant level.

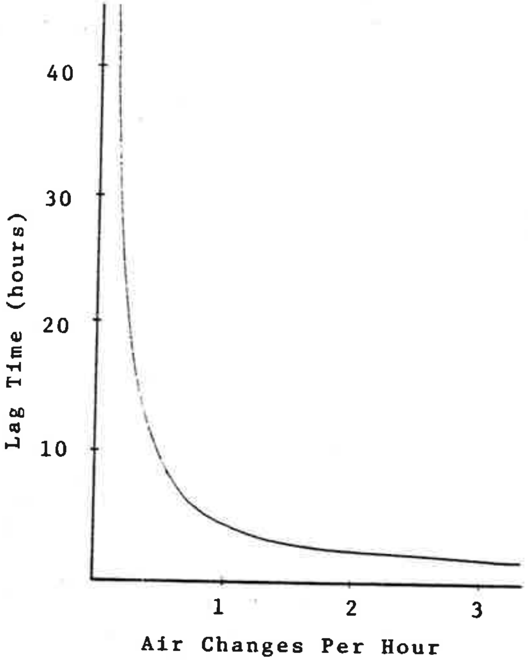

Fig. 2. Lag time to steady state condition as predicted by air exchange rate.

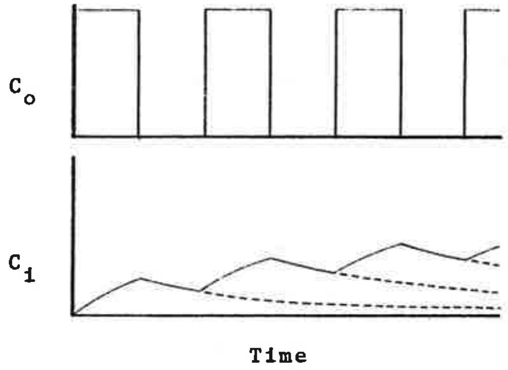

Fig. 3 Superposition of indoor concentrations as the result of multiple outdoor peaks.

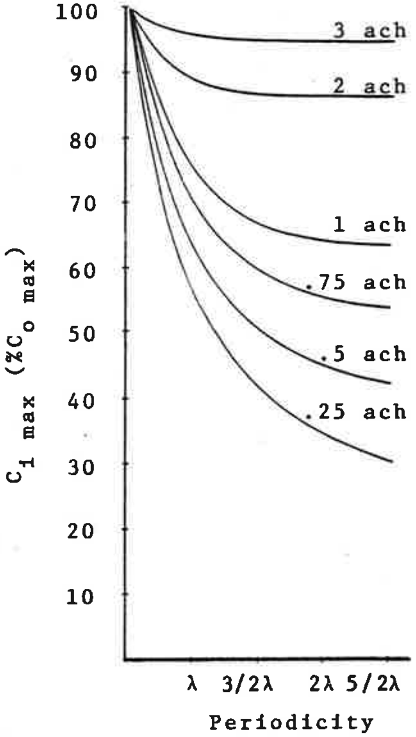

Fig. 4 Indoor maximum pollutant concentration, expressed as percentage of outdoor maximum, as determined by periodicity of outdoor peaks.

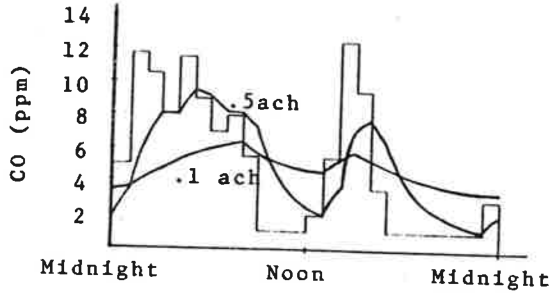

Fig. 5 Predicted indoor levels (ppm) of carbon monoxide from outdoor profile at air exchange rates of 0.1 and 0.5 ach.

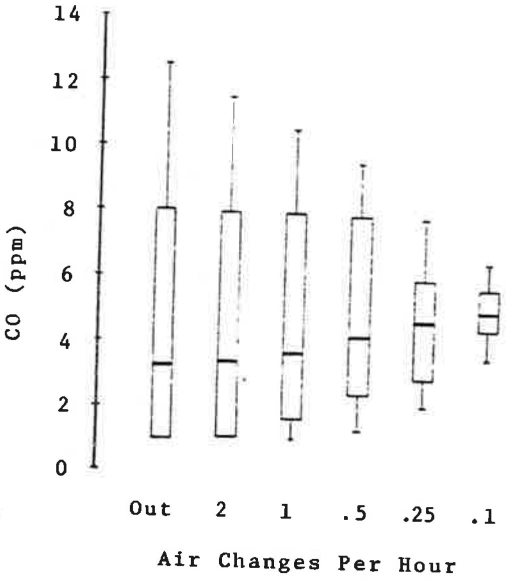

Fig. 6 Box plots of outdoor and indoor concentrations (ppm) for Figure 5 profile. Center bands indicate geometric means, box margins indicate quartiles, and extensions indicate maximum and minimum observations.

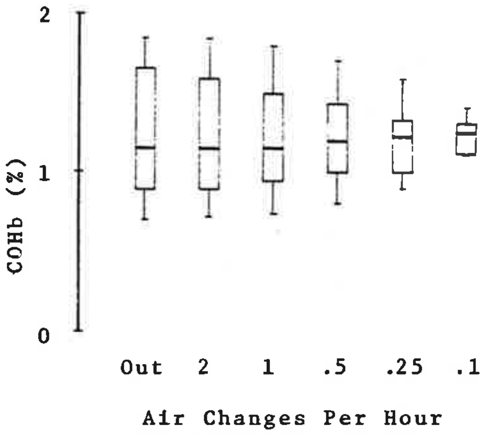

Fig. 7 Box plots of blood carboxyhemoglobin levels (%) for Figure 5 profile. Center bands indicate geometric means, box margins indicate quartiles, and extensions indicate maximum and minimum observations.