MODELING AND MEASUREMENT OF POLLUTANTS INSIDE HOUSES IN PITTSBURGH, PENNSYLVANIA

Cliff I. Davidson, James F. Osborn, and Roy C. Fortmann
Depts. of Civil Engineering, Biomedical Engineering, and Engineering & Public Policy
Carnegie-Mellon University, Pittsburgh, PA 15213 USA

Abstract

Mathematical models for predicting indoor pollutant levels are being developed and compared with measured concentrations in three residential dwellings: a relatively new townhouse constructed according to rigid energy-conservation guidelines, a similar townhouse containing an air-to-air heat exchanger, and a 50-year old house without weatherization. Thus far, efforts have focused primarily on the first residence. The results show that NO, NO_2, and CO emitted from a gas-operated kitchen stove are rapidly mixed throughout the first story of the townhouse, although transport to the upstairs is slower. Concentrations of NO and CO decay slowly with time after the stove is turned off; NO_2 levels decrease much more rapidly. Measurement of emission rates from the stove and estimates of air exchange rates with SF_6 have been used as inputs to a simple one-compartment mass balance model for predicting CO levels. Results of the modeling effort agree reasonably well with measured concentration data, assuming removal of CO only by exfiltration. Besides NO, NO_2, and CO, additional modeling and measurement efforts are currently underway for O_3, SO_2, formaldehyde, respirable and inhalable particles, and volatile organic species.

Introduction

Air pollution levels in the ambient atmosphere have been investigated extensively over the past few decades. Research programs have provided information on sources and sinks, control strategies, atmospheric transport, and human exposure. Our understanding of ambient pollutants is fairly comprehensive in many areas.

In contrast, air pollution in the indoor environment is not well understood. Fewer studies have been conducted, and factors influencing indoor concentrations appear to be even more complex than those affecting ambient levels. Examples of such factors include aspects of building design, indoor sources and sinks, occupant behavior, and outdoor pollutant levels (5).

The current energy problems have increased the need for indoor air pollution studies. Minimizing infiltration during the heating season is a major energy conservation strategy, yet infiltration plays an important role in keeping air pollutants generated indoors at tolerable levels. Developing energy conservation techniques while maintaining clean indoor air is a considerable challenge; a much better understanding of factors influencing indoor air pollution is needed to cope with this problem.

Development of mathematical models, and detailed experimentation to test the models, are necessary to further our understanding of indoor air quality. The models must account for all of the factors having major influence on indoor pollutant concentrations; if key factors are absent or improperly quantified, reliable predictions of air quality in a variety of residences may be impossible. Such comprehensive models are not yet available.

The present study attempts to develop and evaluate indoor air quality models which include several significant parameters. The models are being derived from previously published information covering each factor of interest, and are intended to be used for a variety of residential dwellings. This paper discusses preliminary results of the study, involving experimental testing of simple mass balance relationships in a tightly constructed 1 year old Pittsburgh townhouse. The basic equations are presented first, followed by a discussion of limited experimental data obtained in the townhouse. Finally, the modeling results are compared with measurement data.

Mathematical Relations

Both one and two compartment models are being developed. Figure 1 illustrates the relevant parameters for the simplest form of the one compartment model. The appropriate equation for a pollutant mass balance in the compartment is:

$$V \frac{dC}{dt} = q'C'(1-F') - q'C + S - R \qquad (1)$$

The model assumes complete, instantaneous mixing resulting in a uniform concentration C throughout the house.

A more realistic approach involves dividing the house into two or more compartments. The lower half of Figure 1 illustrates one version of this model, in which the kitchen is considered to be a separate compartment distinct from the rest of the house. A forced-air ventilation system incorporating 100% recycle of building air is included. Equations corresponding to $C_K(t)$ and $C_H(t)$ are similar to Equation 1, and have been presented and discussed by the National Academy of Sciences (5).

One difficulty with using these equations involves the lack of reliable input data for the various parameters. It may be particularly difficult to obtain accurate data on source emissions (S) and removal rates (R) for certain pollutants; quantifying intercompartmental airflows q_{KH} and q_{HK} may pose a problem when using the two-compartment model. For reactive pollutants whose outdoor concentration is appreciable, the proper value for F may be difficult to determine.

A second problem concerns the assumption of complete, instantaneous mixing within each compartment. Nonideal mixing may be studied by monitoring the decay in concentration of an inert tracer gas released within the compartment. Perfect mixing will provide a concentration decrease $C(t) = C_o e^{-q'/V)t}$ as suggested by the solution to Equation 1; deviations between the observed and predicted concentration decay can be accounted for with an empirical mixing factor k, such that $C(t) = C_o e^{-(kq'/V)t}$. Several studies have shown that k may be as small as 0.3, although values are nearly 1.0 for well-mixed rooms (1, 3, 4).

A third problem is that the functional form of these equations implies considerable oversimplification of the true physical and chemical processes being modeled. For example, the mixing factor k underlies our inability to predict true air exchange rates based on characteristics of the building, and on the surrounding windfield and temperature patterns. Values of C', q', R, and S are likely to be complex functions of time. At best, these equations can provide only rough approximations to the true indoor concentrations.

Experimental Data

As of April 1984, the most detailed pollutant data in the townhouse have been obtained for NO, NO_2, and CO. More limited data have been obtained for O_3, SO_2, formaldahyde, inhalable and respirable particles, and volatile organic species. Only data for the first three pollutants are discussed here. Specifications of the equipment used in this study are given by Fortmann et al. (2) in a companion paper for presentation at this conference.

Figure 2 shows the results of a typical monitoring experiment in the townhouse. At time t = 0, one rangetop burner and the oven in the kitchen stove were turned on, and remained on for a period of 60 minutes. Concentrations of NO, NO_2, and CO in the kitchen, living room, and an upstairs bedroom were monitored for five hours beginning at t = 0. Data were thus provided for the rise in pollutant concentrations during stove operation, and for the decay in concentrations after the stove was turned off.

Several characteristics of Figure 2 deserve comment. Note that concentrations in the kitchen and living room are nearly identical for the three pollutants, suggesting that the first story of the townhouse may be considered a single compartment for these conditions. The peak concentrations in the bedroom are smaller than the peak values downstairs, and there is a lag of approximately 15 minutes between upstairs and downstairs peaks for NO and CO. For t > 2 hours, however, the bedroom concentrations of NO and CO are nearly identical to the levels downstairs.

NO_2 shows a rapid decay in concentration after the source emissions are curtailed, probably due to its high reactivity. This reactivity is most likely responsible for keeping the peak NO_2 level in the bedroom far below the peak values downstairs; most of the NO_2 is lost during transport from the kitchen to the upstairs. Nearly identical concentrations of NO_2 are present in all three rooms for t > 75 minutes, which is within 15 minutes after the stove is turned off.

Several similar experiments have been conducted at the townhouse over the past few months. The extent to which modeling can be used to predict the pollutant concentrations observed during these experiments is discussed next.

Comparison of Modeling and Measurement Results

The one and two compartment models discussed earlier are being used to predict pollutant concentrations in the townhouse. A simple example of applying the one compartment model to CO involves the use of Equation 1 with C' and R equal to zero, and with $S(t) = S_o [u(t) - u(t-t_1)]$. S_o is the emission rate of CO (assumed constant for $0 < t < t_1$ while the stove is on), and u(t) is the unit step function having a value of 1.0 for $t > 0$ and a value of zero otherwise. The appropriate solution of Equation 1 for this example is:

$$C(t) = \frac{S_o}{q}(1 - e^{-(q'/V)t})\,u(t) + C_o e^{-(q'/V)t}\,u(t) - \frac{S_o}{q}(1 - e^{-(q'/V)(t-t_1)})\,u(t-t_1) \qquad (2)$$

This equation has been applied to the monitoring experiment for which the data are shown in Figure 3. Values of S_o for the stove in the townhouse have been reported in the companion paper (2); at a gas burn rate of 34 kcal/min used during the experiment, the original data used to construct Table 1 of the companion paper indicate an emission factor of 460 μg CO/kcal, or an emission rate of $S_o = 15$ μg CO/min.

Decay of the inert tracer gas SF_6 (shown in Figure 3) yields an air exchange rate of 0.0047 min^{-1} for a house volume of 240 m^3. Figure 3 also indicates that C_o = 1.9 ppm, and t_1 = 90 min. With these values substituted into Equation 2, the resultant concentration of CO as a function of time is shown in Figure 3. Reasonable agreement between calculated and measured concentrations is observed, although the measured CO levels decay somewhat faster than predicted.

Attempts are currently underway to predict concentrations of other pollutants, particularly NO, NO_2, O_3, and formaldehyde. For these other species, the term R is likely to be significant. Tests are underway to evaluate R for these pollutants. In addition, use of the two compartment model may be necessary during times of poor mixing.

Within the next year, the measurement and modeling efforts will be applied to a similar 1 year old townhouse containing an air-to-air heat exchanger, and to a 50 year old house without weatherization. Results will be presented in subsequent manuscripts. This research is supported by U.S. National Science Foundation grant CEE-8206619 and by U.S. Department of Energy grant 579112-S.

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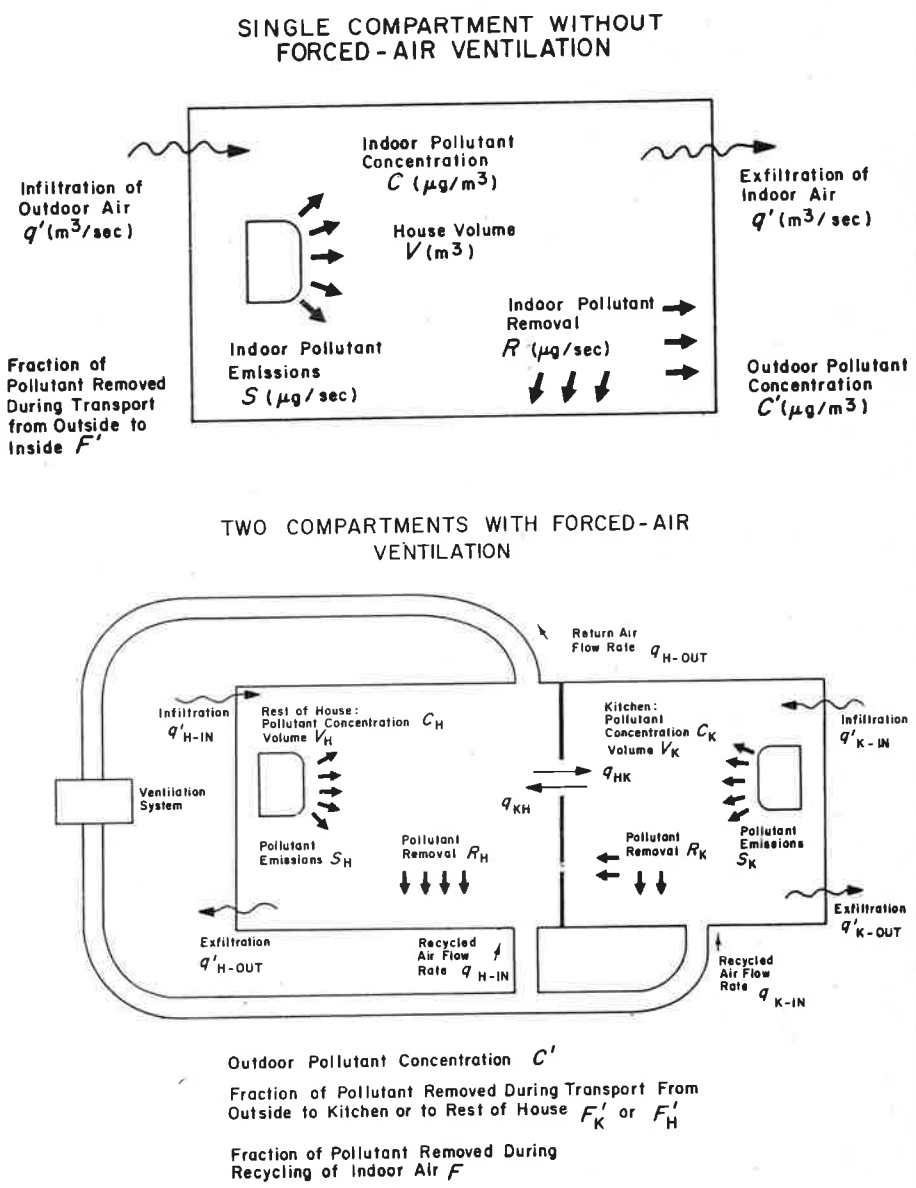

Figure 1. Illustration of parameters influencing indoor pollutant concentrations for the one and two compartment models.

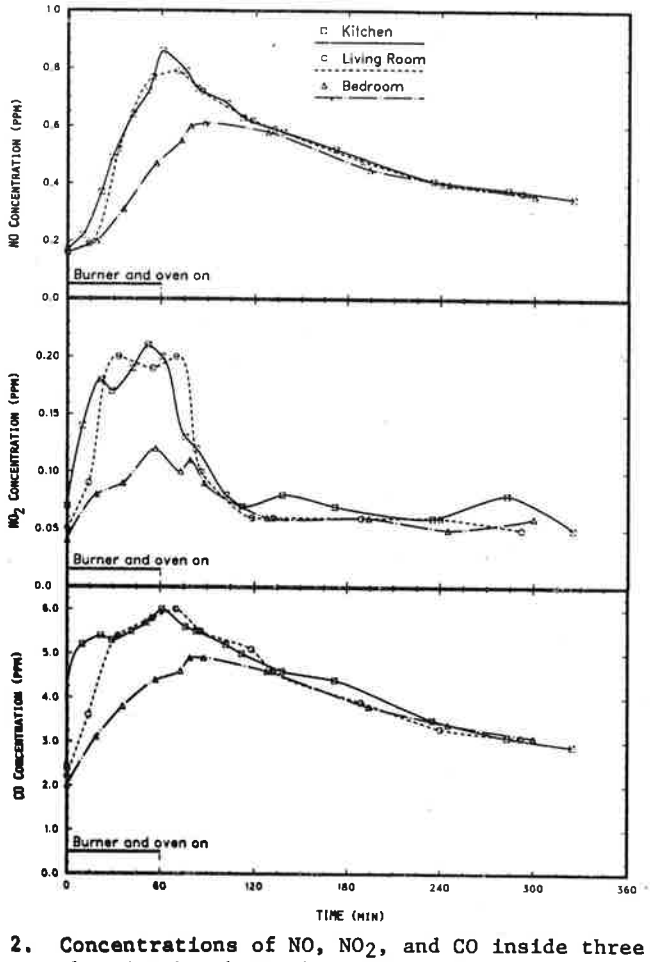

Figure 2. Concentrations of NO, NO_2, and CO inside three rooms of the Pittsburgh townhouse under investigation.

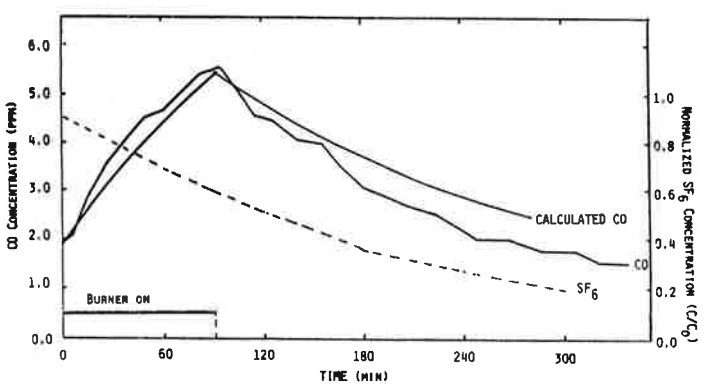

Figure 3. Comparison of calculated and measured concentrations of CO in the townhouse. Data for an air infiltration measurement using SF_6 are also shown.