Title
CONTROLLING INDOOR AIR POLLUTION FROM TOBACCO SMOKE: MODELS AND MEASUREMENTS

Authors
Offermann, F.J.
Girman, J.R.
Sextro, R.G.

Publication Date
1984-07-01

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

Presented at the 3rd International Conference on Indoor Air Quality and Climate, Stockholm, Sweden, August 20-24, 1984

CONTROLLING INDOOR AIR POLLUTION FROM TOBACCO SMOKE: MODELS AND MEASUREMENTS

F.J. Offermann, J.R. Girman, and
R.G. Sextro

July 1984

APPLIED SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

To be presented at The 3rd International
Conference on Indoor Air Quality and Climate,
Stockholm, Sweden, August 20-24, 1984.

LBL-17603
EEB-Vent 84-5

CONTROLLING INDOOR AIR POLLUTION FROM TOBACCO SMOKE: MODELS AND MEASUREMENTS

Francis J. Offermann, John R. Girman, and Richard G. Sextro

Building Ventilation and Indoor Air Quality Program
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

July 1984

This work is supported by the Office of Energy Research, Office of Health and Environment Research, Human Health and Assessments Division and Pollutant Characterization and Safety Research Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Abstract

In this paper we examine the effects of smoking rate, ventilation, surface deposition, and air cleaning on the indoor concentrations of respirable particulate matter and carbon monoxide generated by cigarette smoke. A general mass balance model is presented which has been extended to include the concept of ventilation efficiency. Following a review of the source and removal terms associated with respirable particles and carbon monoxide, we compare model predictions to various health guidelines.

Introduction

Concern has been increasing regarding the potential health effects resulting from chronic exposure to tobacco smoke contaminants. In buildings where smoking is permitted, smoking is the dominant source of respirable particulate matter and to a lesser degree the source of a broad spectrum of gas phase contaminants which include carbon monoxide, ammonia, acrolein, formaldehyde, and many known carcinogens. While direct exposure to mainstream tobacco smoke has been found to be causally related to cancer, cardiovascular disease, and pulmonary disease (1), the effects and dose-response function resulting from exposure to environmental tobacco smoke are less certain. However, increasing information is becoming available which indicates that chronic exposure to tobacco smoke is deleterious to health (2,3,4). In an extensive study of 91,540 Japanese women (2), non-smoking wives of smokers were found to have twice the risk of developing lung cancer than non-smoking women married to non-smokers. Further research is needed to develop a dose-response curve which can be used in conjunction with an indoor contaminant model to establish ventilation rates or other control criteria for acceptable risk. In this paper we examine the various components of a general mass-balance model which can be used to predict indoor contaminant concentrations and to help evaluate the effects of various control strategies or energy conservation measures.

Mass Balance Model

The steady-state indoor concentration, C_{ss}, is determined by the ratio of the production and removal rates:

$$C_{ss} = \frac{PQ_vC_o + S}{E_vQ_v + KV + NE_dQ_d}$$

The following is a brief description of the source and removal terms associated with respirable particles and carbon monoxide from cigarettes and a brief review and assessment of data available as model inputs.

S - Indoor contaminant generation rate (mg/hr). The total indoor emissions are calculated as the sum of the emissions from sidestream and exhaled mainstream smoke. The emissions from each depend on a number of factors including the type and moisture content of the tobacco burned, the amount of tobacco consumed (which depends on butt length), burning rate, puff rate, indoor relative humidity, and depth of inhalation (which affects the amount of mainstream smoke exhaled). However, a reasonable estimate can be made from in situ chamber experiments, knowledge of typical smoking patterns and indoor environmental conditions.

Particulate phase contaminant emissions. There have been few in situ measurements of the amount of respirable particulate matter produced by cigarette smoking. The contribution of exhaled mainstream smoke can be estimated from measurements of mainstream emissions and respiratory deposition. The 1980 sales-weighted average mainstream dry particulate emissions, as reported by the U.S. Federal Trade Commission (FTC) are 14 mg "tar"/cig (5). Including an estimated 1 mg each for the subtracted water and nicotine, the average wet particulate emissions are 16 mg/cig. The respiratory deposition of mainstream particulate matter has been observed by Dalhamn et al. (6), using a cold trap technique, to range from 90-100%. In a more recent study by Hinds et al. (7), respiratory deposition was determined in a more direct manner using standard filtration techniques to range from 22 to 75%, averaging 47%. Assuming an average respiratory deposition of 70%, the average exhaled mainstream emissions are estimated to be 5 mg/cig. Few data are available regarding cigarette sidestream particulate emissions. From chamber experiments reported by Hoegg (8) we calculate sidestream emissions to be 18 mg for a high tar cigarette (34 mg-FTC value) machine smoked at one puff per minute in a 25-m^3 chamber. In a 27-m^3 chamber study by Girman et al. (9) sidestream emissions were observed to be 11 mg/cig for an average tar cigarette (16 mg-FTC) machine smoked at two puffs per minute. These observations are consistent with those reported by Repace (10) for sidestream emissions from smoldering cigarettes (i.e., no puffing) in a 22-m^3 chamber; 9 mg/cig for a medium tar cigarette (17 mg-FTC) and 18 mg/cig for a high tar cigarette (27 mg-FTC). Assuming 10 mg/cig for the sidestream emissions and 5 mg/cig for the exhaled mainstream emissions, the total particulate emissions are estimated to be 15 mg per cigarette. In experiments reported by Cain and Leaderer (11) where the occupants smoked average tar cigarettes (17 mg-FTC value) in a 35-m^3 chamber we calculate average emissions of 11 mg/cig. However, since these cigarettes were prematurely extinguished after 7.5 minutes of smoking, an emission rate corresponding to the accepted average burning time of 10 minutes/cig (1) is estimated to be 15 mg/cig, consistent with our previously derived estimate. Interestingly, this is less than half the sidestream emissions widely reported by researchers using small (e.g., 250 ml) water cooled collection vessels (1, 12). These chambers directly collect the sidestream emissions and appear to overestimate emissions when compared to actual <u>in situ</u> test measurements.

Carbon monoxide (CO) emissions. Based on an estimated sales-weighted average mainstream emissions of 14 mg/cig (5), 50% retention by the smoker (7), and estimated sidestream emissions of 78 mg/cig (9), the total emissions of CO are estimated to be 85 mg/cig.

PQ_vC_o - <u>Outdoor source term (mg/hr).</u> The outdoor contribution to indoor concentrations can be calculated from the product of an empirically determined penetration factor, P, the ventilation rate Q_v, and the outdoor concentration C_o. A penetration factor of 1.0 is reasonable for a non-reactive gas such as CO or for respirable size particles where the supply air does not pass through a filter designed to remove these particles. For contaminants where the indoor concentration is much greater than the outdoor concentration, the outdoor source term may be assumed to be zero.

E_vQ_v - <u>Removal by ventilation (m^3/hr).</u> The rate of removal by ventilation is calculated as the product of the ventilation efficiency parameter, E_v, and the ventilation rate, Q_v. The ventilation efficiency term, E_v, as originally defined by Rydberg (13), and later discussed by Sandberg (14), is the ratio of the exhaust concentration to the mean concentration of the occupied space. In the past, researchers have incorporated a "mixing factor" to account for the observed differences between removal rates with and without perfect mixing. In tests conducted by Drivas et al. (15), mixing factors were determined using tracers to be in the range of 0.3 to 0.7.

However, these tests were conducted at unusually high ventilation rates (i.e., 13-16 air changes/hr) where mixing problems would be anticipated. In the more typical range of 0.5-3.0 air changes per hour, Revzan (16) has measured values of E_v for a point source of tracer gas with window exhaust which range from a minimum of 1.0 at the lower ventilation rates to as much as 2.0 at 3 ach. For the case of a heated buoyant source, such as the sidestream emissions from a cigarette with direct-overhead exhaust, ventilation efficiencies may be substantially greater. In commercial office buildings, where up to 80% of the air is recirculated, mixing is generally good and a ventilation efficiency of 1.0 is a reasonable assumption.

K - Natural decay rate (hr^{-1}). Contaminants may be removed by mechanisms other than ventilation. These mechanisms include surface deposition, chemical transformation, and radioactive decay. The natural removal rate, K, is determined empirically from chamber decay experiments where the contaminant decay rates are compared to those observed for an inert tracer (i.e., K=0).

Respirable particulate matter. The dominant particulate mass removal mechanism other than ventilation is surface deposition. In experiments conducted in a 34-m^3 chamber the surface deposition rate for tobacco smoke particles was observed to be just 0.1 hr^{-1} based on mass (17). Results of tests conducted with and without the operation of mixing fans were similar. These results agree with data reported by others (8, 9) and are consistent with what we would expect based on particle deposition theory (18). The surface deposition rate of particles depends on both the rate of convective transport within the enclosure and the rate of diffusive transport across the laminar surface boundary layer. For cigarette smoke particles the deposition rate is limited by the diffusive transport rate because of the diffusion coefficients associated with tobacco smoke particles are very small, 2×10^{-6} to 2×10^{-7} cm^2/sec. Tobacco smoke particles are too large for diffusional effects and too small for sedimentation or inertial effects to be significant. It should also be noted that the deposition rate is a function of the surface-to-volume ratio of the chamber. Higher deposition rates can be expected to occur in very small chambers and lower deposition rates in very large spaces. The surface-to-volume ratio for the 34-m^3 chamber results reported here (7) is 2 m^{-1}, typical of a modestly furnished office. The average mass deposition rate of 0.1 m^{-1} thus translates into an effective deposition velocity of 1.4×10^{-3} cm/sec.

Carbon monoxide. The natural decay rate indoors for non-reactive contaminants such as carbon monoxide is zero.

NE_dQ_d - Removal by air cleaning. The rate of removal by air cleaning is calculated as the product of the contaminant removal efficiency; N, the device ventilation efficiency, E_d; and the device air flow rate Q_d. The contaminant removal efficiency is calculated as one minus the ratio of outlet to inlet concentrations. The device ventilation efficiency is the ratio of the exhaust concentration to the mean concentration of the occupied zone. Electrostatic precipitators and high efficiency fibrous filters are effective in removing the particulate phase contaminants of cigarette smoke. Particulate removal efficiencies from 50-100 percent have been reported (17). Removing the gas phase constituents of tobacco smoke, which comprise approximately two thirds of the contaminants mass, is much more difficult. While various air cleaning systems are effective at removing some of the toxic gases present in tobacco smoke, there are no practical air cleaning systems for removing a contaminants such as carbon monoxide. These contaminants are best removed by ventilation which is 100 percent effective at removing all gases.

Application of the Model to Determine Ventilation Requirements

Figure 1 is a plot of the steady-state indoor concentrations of tobacco smoke particles and carbon monoxide as a function of the effective ventilation rate ($E_vQ_v + KV + NE_dQ_d$) per smoker predicted from equation 1 using average emission rates per smoker of 30 mg/hr for particulate matter and 170 mg/hr per smoker for CO (2 cigarettes per hour-smoker). From this analysis a minimum effective ventilation rate of 75 m^3/hr is required for each smoker to maintain steady-state particulate concentrations below the level where the smoke is visible (i.e. $\sim$ 400 $\mu g/m^3$). The corresponding carbon monoxide concentration at this ventilation rate is 2.3 mg/m^3, well below the National Ambient Air Quality Standard (NAAQS) of 10 mg/m^3. An effective ventilation rate of 115 m^3/hr per smoker is required to maintain particulate concentrations below the NAAQS 24-hour standard of 260 $\mu g/m^3$ (to be exceeded only once per year) or 400 m^3/hr if the NAAQS annual standard of 75 $\mu g/m^3$ is to be met. However, even this amount of ventilation may be inadequate to protect nonsmokers since applying outdoor standards to indoor concentrations of smoke particles may not be appropriate given differences in chemical composition, mutagenic activity, and size distribution of outdoor particles and tobacco smoke particles. The current minimum recommended ventilation rate, as proposed by ASHRAE (19), is 34 m^3/hr per person for office buildings where smoking is permitted. Assuming one out of three occupants are smokers (1), 7 occupants per 300 m^3 (19), a tobacco smoke surface deposition rate of 0.1 hr^{-1}, the effective ventilation rate is 115 m^3/hr per smoker which corresponds to an indoor steady-state concentration of 261 $\mu g/m^3$. The concentration predicted by a phenomenological model proposed by Repace (20) for the same office scenario is 187 g/m^3, 28 percent less than that predicted by the model presented here. The discrepancy arises from differences in the particulate emissions per cigarette assumed in each model.

Summary and Conclusions

We have presented a general mass-balance model useful for predicting indoor steady-state concentrations and have examined the source and removal terms for particulate matter and carbon monoxide generated from cigarette smoking. Based on a review of available data, we recommend an emission rate of 15 mg/cig for respirable particulate matter and 85 mg/cig for carbon monoxide. Natural removal by means other than ventilation is small for tobacco smoke particles, 0.1 hr^{-1} based on mass and zero for carbon monoxide. Based on these inputs, the minimum ventilation rates recommended by ASHRAE for offices where smoking is permitted result in concentrations of respirable particulate matter three times the NAAQS annual standard of 75 $\mu g/m^3$. At present there are no standards based upon the health effects associated with cigarette smoke. More effort should be spent working with the large epidemiological studies where increased health risks from environmental tobacco smoke exposure have been observed. Estimates of the exposure received by these populations may provide valuable information with regards to the establishment of recommended ventilation rates based on acceptable risk.

Acknowledgement

This work is supported by the Office of Energy Research, Office of Health and Environment Research, Human Health and Assessments Division and Pollutant Characterization and Safety Research Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

(1) U.S. Department of Health, Education and Welfare. Smoking and Health: A report of the surgeon general. Publ. 79-50066, Dept. of Health, Education, and Welfare, Washington, D.C., 1979.

(2) Hirayama, T. Non-smoking wives of heavy smokers have a higher risk of lung cancer: a study from Japan. British Medical Journal, 1981, 282, 183-185.

(3) Trichopoulos, D., Kalandidi, A., Sparros, L., and McMahon, B. Lung cancer and passive smoking. International Journal of Cancer, 1981, 27, 1-4.

(4) Correa, P., Pickle, L.W., Fonham, E., Lin, Y., and Haenszl, W. Passive smoking and lung cancer, Lancet, 1983, II, 595-597.

(5) U.S. Federal Trade Commission. Report to Congress pursuant to the federal cigarette labeling and advertising act for the year of 1980. U.S. Federal Trade Commission, Washington, D.C., 1982.

(6) Dalhamn, T., Edfors, M., and Rydander, R. Retention of cigarette smoke in human lungs. Arch. Envirn. Health, 1968, 17, 746-748.

(7) Hinds, W., First, M.W., Huber, G.L., and Shea, J.W. A method for

measuring respiratory deposition of cigarette smoke during smoking. Am. Ind. Hyg. Assoc. J., 1983, 44, 113-118.

(8) Hoegg, U.R. Cigarette smoke in closed spaces. Environmental Health Perspectives, 1972, 2, 117-128.

(9) Girman, J.R., Apte, M.G., Traynor, G.W., and Hollowell, C.D. Pollutant emission rates of indoor combustion appliances and sidestream cigarette smoke. Environment International, 1982, 8, 213-221.

(10) Repace, J.L., and Lowery, A.H. Tobacco smoke, ventilation, and indoor air quality. ASHRAE Transactions, 1982, 88, 894-914.

(11) Cain, W.S., and Leaderer, B.P. Ventilation requirements in occupied spaces during smoking and nonsmoking occupancy. Environment International, 1982, 8, 505-514.

(12) Committee on Indoor Pollutants, Indoor Pollutants. National Academy Press, Washington D.C., 1981.

(13) Rydberg, I., and Kulman, E. Ventilationens effektivitet vid olika placeringar av inblasnings- och utsugningsoppningarna, 1947, VVS, No. 3.

(14) Sandberg, M. What is ventilation efficiency? Building and Environment, 1981, 16, no. 2, 123-135.

(15) Drivas, P.J., Simmonds, P.G., and Shair, F.H. Experimental characterization of ventilation systems in buildings, Environmental Science and Technology, 1972, 6, no. 7, pp. 609-614.

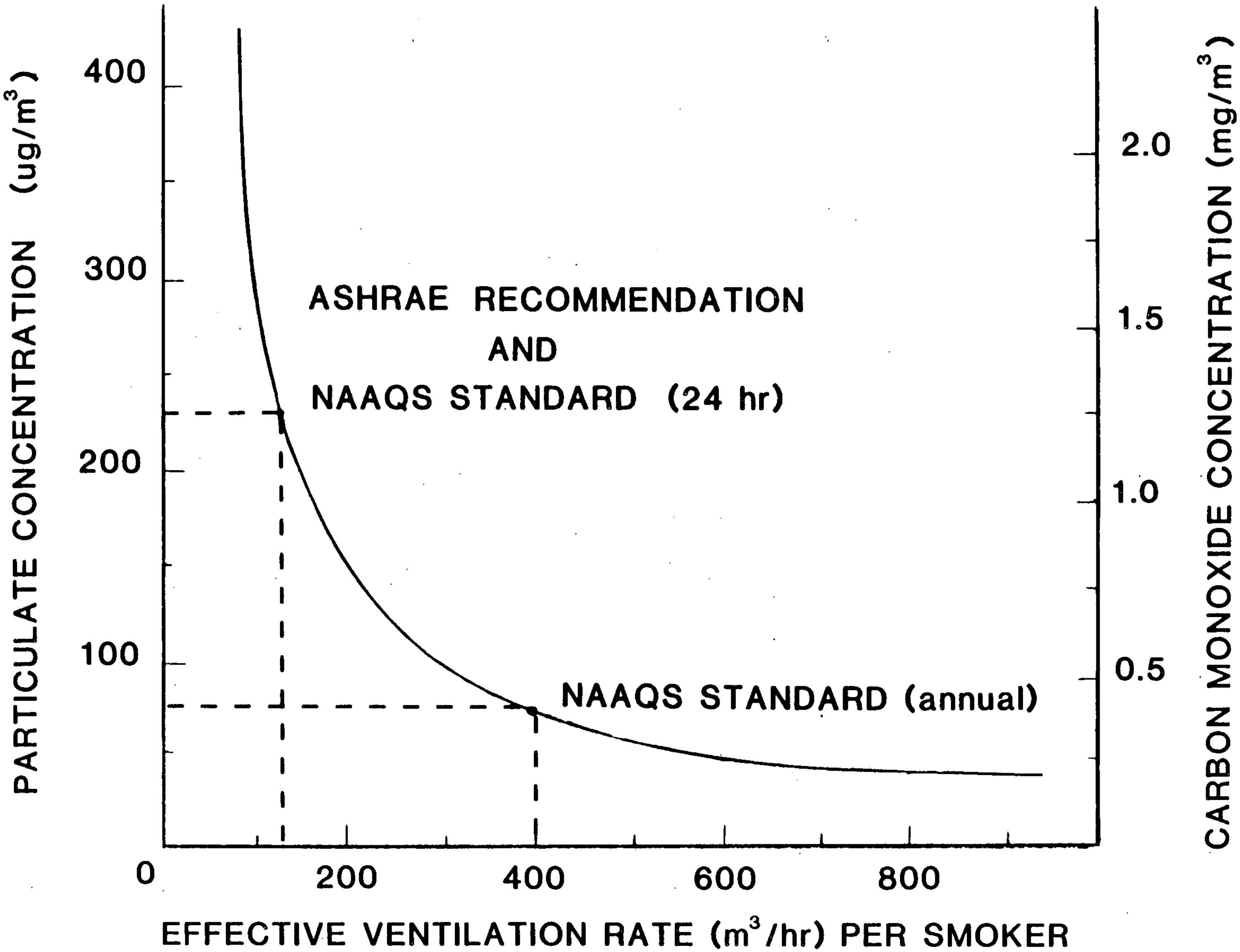
(16) Revzan, K.L. Effectiveness of local ventilation in removing simulated pollution from point sources. Lawrence Berkeley Laboratory Report LBL-16701, Berkeley, Ca 1983.

(17) Offermann, F.J., Sextro, R.G., Fisk, W.J., Nazaroff, W.W., Nero, A.V., Revzan, K.L., and Yater, J. Control of respirable particles and radon progeny with portable air cleaners. Lawrence Berkeley Laboratory Report LBL-16659, Berkeley, CA, 1984.

(18) Fuchs, N.A., The mechanics of aerosols. Pergamon Press, 1964, 250-257.

(19) ASHRAE Standard 62-1981. Ventilation for acceptable indoor air quality. American Society of Heating, Refrigeration, and Air Conditioning Engineers. Atlanta, Georgia, 1981.

(20) Repace, J.L., and Lowery, A.H. Indoor air pollution from tobacco smoke and public health. Science, 1980, 280, 464-472.



XBL 847-2895

Figure 1. Steady-state indoor concentrations of respirable particulate matter and carbon monoxide as a function of effective ventilation rate and assuming a smoking rate of two cigarettes per hour-smoker and emissions of 15 mg particulate matter and 85 mg carbon monoxide per cigarette.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720