行政院國家科學委員會專題研究計畫　期中進度報告

自然通風建築中不同粒徑顆粒物質室內/室外/人體暴露之關係(2/3)

計畫類別：個別型計畫
計畫編號：NSC93-2313-B-002-030-
執行期間：93年08月01日至94年07月31日
執行單位：國立臺灣大學生物環境系統工程學系暨研究所

計畫主持人：廖中明

報告類型：精簡報告

處理方式：本計畫可公開查詢

中　華　民　國 94年5月31日

行政院國家科學委員會專題研究計畫期中報告

自然通風建築中不同粒徑顆粒物質室內/室外/人體暴露之關係(2/3)

計畫編號：NSC 93－2313－B－002－030
執行期限：93/08/01~94/07/31
執行單位：國立台灣大學生物環境系統工程學系
主 持 人：廖中明

摘要

第二年的研究主要是發展區塊模式描述通風建築內不同粒徑的顆粒於人體呼吸道之暴露動態行為。人體呼吸道主要考慮由五區塊所組成，分別為(1)鼻腔區(2)口腔咽喉區(3)氣管支氣管區(4)細微支氣管區(5)肺泡區。顆粒在人體呼吸道之傳輸機制包括呼吸、重力沉降、紊流擴散沉澱、慣性衝擊、接觸附著及清除損失。後續將經由區塊模式的發展探討氣管支氣管區、細微支氣管區以及肺泡區三處的顆粒濃度與室內顆粒濃度比值，並比較在顆粒粒徑 0.01–10 μm 範圍，經由鼻腔呼吸與口腔呼吸的沉澱分量以及暴露劑量。

關鍵詞：顆粒物質，區塊模式，肺部顆粒濃度/室內顆粒濃度比值。

Abstract

The objective of this project in the second year is to develop a size-dependent compartmental model to describe airborne particulate matter (PM) exposure dynamics in human respiratory tract (HRT) in ventilated buildings. HRT was divided into five major compartments: (1) the nasal passage (ET1); (2) the pharynx (ET2); (3) the bronchial region (BB); (4) the bronchiolar region (bb); and (5) the alveolar-interstitial region (AI). Transport mechanisms of airborne PM in HRT include respiration, gravitational settling, turbulent diffusive deposition, inertial impaction, interception deposition loss, and PM clearance. We hope to estimate airborne PM mass lung/indoor ratios in the bronchial region, the bronchiolar region, and the alveolar-interstitial region, deposition fraction and exposure dose in the size ranges 0.01–10 µm via nosal or oral breathing in the near future.

Keywords: Particulate matter; Compartmental model; Lung/Indoor ratio

Introduction

Outdoor PM attributable to the indoor air in urban/suburban residence houses has been the most serious indoor air pollution in Taiwan region (Li and Lin, 2002). There is extensive evidence to suggest that exposure to increased levels of inhalable particulate pollutants is associated with increases in mortality and morbidity from cardiovascular and respiratory causes (Pope and Dockery, 1992; Seaton et al., 1995). The relationship between exposure to airborne PM and resulting health effects is the subject of an ever-increasing number of studies. Guo et al. (1999) revealed that PM_{10} was positively associated with the prevalence of asthma in middle-school students in Taiwan. Hwang and Chan (2002) demonstrated that rates of daily clinic visits were associated with current-day concentrations of PM_{10} in Taiwan region.

Numerous mathematical models for predicting particle deposition in the human airway are developed to include airflow dynamic, physiological, lung morphological, and dose-cumulated submodels. In general, particle deposition models in the human airway can be classified into three major groups. The first follows an approach based on the concept of applying compartmental modeling to human lung anatomy. In the second approach, the human lung is modeled as a chamber shaped like a trumpet with a variable crosssectional area, and the third approach used a combination of theoretical and empirical expressions to predict particle deposition in HRT (Lazaridis et al., 2001), whereas the third approach was suggested by ICRP66 (1994). Jacquez (1996) further indicated that the compartmental model was used in biology and can be found in such diverse areas as epidemiology, pharmacokinetics, intermediary metabolism, carcinogenesis, mutation rate and evolution, and physical sciences.

The purposes of this study are twofold: (1) to determine the airborne PM mass lung/indoor (L/I) ratio under steady-state based on the measurements of airborne PM characteristics, including size distribution patterns, mass, and number concentrations in buildings, and (2) to calculate the deposition fractions and exposure dose of airborne PM for different HRT regions that can be used for developing risk analysis of long-term inhalation in buildings.

Model Development

Airborne Dust Deposition Model

HRT was divided into five major compartments from the suggestion of ICRP66 (1994): (1) the nasal passage (ET1), comprising the anterior nose and the posterior nasal passages; (2) the pharynx (ET2), comprising the larynx and mouth; (3) the bronchial region (BB), comprising the airway from the trachea, main bronchi, and intrapulmonary bronchi; (4) the bronchiolar region (bb), comprising the bronchioles and terminal bronchioles; and (5) the alveolar-interstitial region (AI), comprising the airway from the respiratory bronchioli through the alveolar sacs. Before deriving the system dynamic equations to describe PM concentration variation within HRT, the following assumptions were made: (1) each compartment is assumed to be a completely mixing system; (2) airborne dust is treated as an aerodynamic equivalent sphere and is electrically neutral; (3) no gas-to-dust conversion occurs within the system; (4) HRT is treated as a circular tube with the same physiological characteristics within the same compartment; (5) turbulent coagulation and hygroscopicity of the dust phase are neglected; and (6) air volume changes caused by oxygen demand in HRT are neglected.

Combining the physical and physiological processes controlling the gain and loss rates yields the dynamics equations that describe the concentration trajectory of airborne dust in HRT. Followed by the principle of mass balance, the dynamic equations of the inspiratory oral cavity (IOC) varying with dust size range k and time t to each regional compartment are given by a state-space realization form of a linear dynamic equation. We employed a lung/indoor (L/I) ratio model (Liao et al., 2003) to calculate the PM L/I ratio,

$$\frac{C_1(k,t)}{C_I(k,t)}=\frac{-\frac{Q}{V_1}\cdot\left(L_{33}\cdot L_{44}\cdot L_{55}-L_{33}\cdot\beta_{45}\frac{Q}{V_4}\beta_{54}\frac{Q}{V_5}-L_{55}\cdot\beta_{34}\frac{Q}{V_3}\cdot\beta_{43}\frac{Q}{V_4}\right)}{\| L(k)\|} \tag{1}$$

$$\frac{C_3(k,t)}{C_I(k,t)}=\frac{\frac{Q}{V_1}\cdot\beta_{31}\frac{Q}{V_3}\cdot\left(L_{44}\cdot L_{55}-\beta_{45}\frac{Q}{V_4}\cdot\beta_{54}\frac{Q}{V_5}\right)}{\| L(k)\|}$$

$$\frac{C_4(k,t)}{C_I(k,t)}=\frac{-\frac{Q}{V_1}\cdot\beta_{31}\frac{Q}{V_3}\cdot\beta_{43}\frac{Q}{V_4}\cdot L_{55}}{\| L(k)\|}$$

$$\frac{C_5(k,t)}{C_I(k,t)}=\frac{\frac{Q}{V_1}\cdot\beta_{31}\frac{Q}{V_3}\cdot\beta_{43}\frac{Q}{V_4}\cdot\beta_{54}\frac{Q}{V_5}}{\| L(k)\|}$$

where $C_i(k,t)/C_I(k,t)$, i= 1–5; represents the PM L/I ratios for compartments ET_1, ET_2, BB, bb, and AI, respectively, Q is the breathing rate (cm^3 h^{-1}); V_i is the volume of compartment i (cm^{-3}); β_{mn} is the transition coefficient from compartments n to m; the constant input matrix $[B]=\mathrm{diag}[Q/V_1, 0, 0, 0]$, and $\|L(k)\|$ is a determinant of $[L(k)]$ with the form as

$$\begin{bmatrix}
\begin{array}{c}-\lambda_{d_1}(k)-\lambda_{s_1}(k)-\lambda_{im_1}(k)\\ -\varepsilon_1(k)\frac{Q}{V_1}-\beta_{31}\frac{Q}{V_1}-\frac{Q}{V_1}\end{array} & \beta_{13}\frac{Q}{V_1} & 0 & 0 \\
\beta_{31}\frac{Q}{V_3} & \begin{array}{c}-\lambda_{d_3}(k)-\lambda_{s_3}(k)-\lambda_{im_3}(k)\\ -\varepsilon_3(k)\frac{Q}{V_3}-\beta_{43}\frac{Q}{V_3}-\beta_{13}\frac{Q}{V_3}\end{array} & \beta_{34}\frac{Q}{V_3} & 0 \\
0 & \beta_{43}\frac{Q}{V_4} & \begin{array}{c}-\lambda_{d_4}(k)-\lambda_{s_4}(k)-\lambda_{im_4}(k)\\ -\varepsilon_4(k)\frac{Q}{V_4}-\beta_{54}\frac{Q}{V_4}-\beta_{34}\frac{Q}{V_4}\end{array} & \beta_{45}\frac{Q}{V_4} \\
0 & 0 & \beta_{54}\frac{Q}{V_5} & \begin{array}{c}-\lambda_{d_5}(k)-\lambda_{s_5}(k)-\lambda_{im_5}(k)\\ -\varepsilon_5(k)\frac{Q}{V_5}-\beta_{45}\frac{Q}{V_5}-C_L(t)\end{array}
\end{bmatrix} \tag{2}$$

where $\lambda_{di}(k)$, $\lambda_{si}(k)$, and $\lambda_{imi}(k)$ represent turbulent diffusive deposition rate, gravitational settling rate, and inertial impaction rate, respectively, in the k^{th} size range in the compartment i (s^{-1}); $\varepsilon_i(k)$ is the interception deposition efficiency in the k^{th} size range in the compartment i; $C_L(t)$ is the time-dependent PM clearance rate in the compartment AI (s^{-1}), and $L_{ii} = L_{ii}(k)$ is the diagonal element of $[L(k)]$.

PM deposition estimations

The deposition model used to describe indoor PM deposition in a naturally ventilated airspace is derived from Crump and Seinfeld (1981) and is referred to as the C-S model. The turbulent flow paradigm appears to be best applicable to the building scenario where ventilation (natural or forced) is the primary source of turbulence. The C-S model is a well-established general model for calculating aerosol deposition rate due to turbulent diffusion, Brownian diffusion, and gravitational sedimentation in a turbulently mixed arbitrary shape of airspace.

We also employed a time-dependent model to estimate PM size-dependent deposition rate from our data collections to make a comparison between theoretical (i.e., C-S model) and empirical determined values. Estimates obtained from data collected during periods with constant air exchange rates. An exponential equation was used to describe indoor PM deposition in constant air exchange rates and outdoor concentrations during the decay period and that indoor concentrations are well-mixed (Abt et al., 2000; Howard-Reed et al., 2003),

$$C_{(t)}(k)=e^{-(\lambda_n+\lambda_{d,m}(k))t}C_{(t-1)}(k) \tag{3}$$

where $C_{(t)}(k)$ and $C_{(t\text{-}1)}(k)$ are the size-dependent indoor concentrations at times t and $t\text{-}1$, respectively (μg m^{-3}); $\lambda_n+\lambda_{d,m}(k)$ may refer to as the overall system decay rate (h^{-1}); and $\lambda_{d,m}(k)$ is the size-dependent PM deposition rate estimates (h^{-1}). The deposition rates for these PM may be determined when the source generated by a certain indoor activity (e.g., cooking) was stopped. Deposition rates are estimated by taking the natural logarithm of both side of Eq. (3) for a given PM size range, and Eq. (3) can be written as

$$\ln C_{(t)}(k)=-(\lambda_n+\lambda_{d,m}(k))t+\ln C_{(t-1)}(k)\,. \tag{4}$$

PM inhalation dose in HRT

The time-dependent concentration profiles of PM are used to calculate exposure dose through inhalation and represented as

$$D_d(k,t)=\frac{\int_0^t C_i(k,t)\cdot d_F(k)\cdot Q\,dt}{A_i} \tag{5}$$

where $D_d(k,t)$ is the time-dependent cumulative inhalation dose rate of PM per unit area of each lung region in the k^{th} size range (particles cm^{-2} h^{-1}); A_i is the surface area of airway wall in the compartment i (cm^2); and $d_F(k)$ is the PM deposition fraction of each lung region in the k^{th} size range with the form as

$$d_F(k,t)=\frac{C_i(k,t)}{C_I(k,t)}\left[\left(\lambda_{d_i}(k)+\lambda_{s_i}(k)+\lambda_{im_i}(k)\right)\cdot\frac{V}{Q}+\varepsilon_i(k)\right]. \tag{6}$$

The differences in exposure scenarios can vary due to factors such as diameter of airways, breathing rate, PM profile, and the time spent in the houses.

References

- Abt, E., Suh, H.H., Catalano, P., Koutrakis, P. 2000. Relative contribution of outdoor and indoor particle sources to indoor concentrations. Environmental Science and Technology 34: 3579-3587.
- Crump, J.G., Seinfeld, J.H. 1981. Turbulent deposition and gravitational sedimentation of an aerosol in a vessel of arbitrary shape. Journal of Aerosol Science 12: 405-415.

Guo, Y., Lin, Y.C., Sung, F.C., Huang, S.L., Ko, Y.C., Lai, J.S., Su, H.J., Shaw, C.K., Lin, R.S., Dockery, D.W. 1999. Climate, traffic-related air pollutants, and asthma prevalence in middle-school children in Taiwan. Environmental Health Perspectives 107: 1001-1006.

Howard-Reed, C., Wallace, L.A., Emmerich, S.J. 2003. Effect of ventilation systems and air filters on decay rates of particles produced by indoor sources in an occupied townhouse. Atmospheric Environment 37: 5295-5306.

Hwang, J.S., Chan, C.C. 2002. Effects of air pollution on daily clinic visits for lower respiratory tract illness. American Journal of Epidemiology 155: 1-10.

ICRP. 1994. Human respiratory tract model for radiological protection, a report of a task group of the International Commission on Radiological Protection. ICRP Publication No. 66, Elsevier, New York.

Jacquez, J.A. 1996. Compartmental analysis in biology and medicine, 3rd ed., BioMedware, Ann Arbor, Michigan.

Lazaridis, M., Broday, D.M., Hov, O., Georgopoulos, P.G. 2001. Integrated in the human respiratory tract. Environmental Science ane Technology 35: 3727-3734.

Li, C.S., Lin, C.H. 2002. PM1/PM2.5/PM10 characteristics in the urban atmosphere of Taipei. Aerosol Science and Technology 36: 469-473.

Liao, C.M., Chen, J.W., Huang, S.J. 2003. Size-dependent PM_{10} indoor/outdoor/personal relationships for a wind-induced naturally ventilated airspace. Atmospheric Environment 37: 3065-3075.

Pope, C.A., Dockery, D.W. 1992. Acute health effects of PM_{10} pollution on symptomatic and asymptomatic children. American Review of Respiratory Disease 145: 1123-1128.

Seaton, A., MacNee, W., Donalden, K., Godden, D. 1995. Particulate air pollution and acute health effects. Lancet 345: 176-178.