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Practical approaches to determine ventilation rate for offices while considering physical and chemical variables for building material emissions

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ABSTRACT

Indoor air pollutants in offices can be attributed to various sources, including building materials, consumer products, and exhalation from occupants. The required ventilation rate for offices can be determined by estimating the majority of emissions originated from building materials, as an additional determinant factor for ventilation rate, with the assumption of constant ventilation with 100% outdoor air, uniform indoor mixing, and no chemical reactions. In this paper, the validity of these assumptions was investigated by incorporating the effects of various physical and chemical factors in determining material emissions and ventilation rates. Three physical factors investigated were recirculation ventilation, intermittent ventilation and pollutant distribution. Simplified methods using correction factors were proposed to revise the ventilation rate and validated by emission modeling and CFD method. In addition, three chemical factors were discussed. First, 28 building materials were selected from the NRC database and each was subject to determining the ventilation rate. As a result, 28 leading pollutants that are likely to determine the ventilation rate were obtained. Because most of the leading pollutants are reactants rather than products of indoor air reactions, it was concluded that the current ventilation rate determining methods should still be applicable. Additionally, a correction method was proposed for a reaction product such as formaldehyde. Second, the methods to revise ventilation rate based on temperature variation and pollutant concentration in outdoor air were proposed. This study showed that ventilation rate for offices could be determined based on building material emissions in more realistic ventilation and environmental conditions.

1. Introduction

The indoor environment is susceptible to contaminants and usually more polluted than outdoor air due to indoor sources such as humans, open fires, building materials, consumer products, indoor activities, and so on [1–4]. It is widely reported that indoor pollution can adversely affect human health, comfort and productivity, and even be the cause of excessive morbidity and mortality [5,6]. Although outdoor air also contains contaminants, usually at lower concentrations [7,8], that are originated from traffic exhaust, industry, etc. [9,10], ventilation with outdoor air is still the basic means to remove pollutants emitted from various indoor sources, thereby reducing their concentrations in occupied spaces and achieving better indoor air quality [11,12]. However, because of transient nature of indoor air quality partly due to the ever-changing emission sources and indoor air chemistry, as well as the increasing demand of efficient use of energy, setting an adequate ventilation rate for buildings is still in question.

Throughout the history of ventilation, ventilation rate is prevailingly stated as the term of minimum air change rate (ACH) per person for at least two reasons. First, it is reasonable and convenient to determine ventilation rate based on the number of occupants since the health of the occupants is the objective of ventilation in most cases [4,13,14]. Second, humans were considered as the main source for indoor pollution ever since Yaglou et al.'s experiments on the relationship between occupants, perceived indoor air quality and ventilation rates [15,16]. Consequently, the issue of how much the air change rate per person is appropriate at different times has become important worldwide. For instance, the ACH per occupant, which is termed as the conventional method, in indoor air quality standards or regulations for

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Nomenclature

Symbols

A_1, A_2	independent and empirical parameters in Eqs. (17) and (18)
A_i	exposed surface area of the i-th building material (m^2)
A_d	indoor surface area for the ozone deposition (m^2)
A_z	the net occupiable floor area of the ventilation zone (m^2)
$C_{0,i,j}$	initial material-phase emittable concentration for the j-th pollutant in the i-th building material ($\mu g \cdot m^{-3}$)
$C_{i,j,\infty}(t)$	material-phase concentration for the j-th pollutant at the top of the i-th building material when emissions reach steady-state ($\mu g \cdot m^{-3}$)
CR_j	characteristic frequency of the j-th leading pollutants (fractional)
$D_{i,j}$	material-phase diffusion coefficient of the j-th pollutant emitted from i-th building material ($m^2 \cdot s^{-1}$)
E_{bz}	pollutant distribution effectiveness coefficient (dimensionless)
$E_{i,j}$	steady-state hourly emission rate for the j-th pollutant in the i-th building material ($\mu g \cdot h^{-1}$)
$\overline{E}_{AB,n}$	the average pollutant hourly emission rate of the n-th periodic cycle in intermittent ventilation ($\mu g \cdot h^{-1}$)
f	the duration time for one ventilation period (in intermittent ventilation) divided by the cycle time (fractional)
h_m	convective mass transfer coefficient ($m \cdot s^{-1}$)
H	a lumped variable in Eq. (4), $H = h_m / D_{i,j} K_{i,j}$ (m^{-1})
$K_{i,j}$	material/air partition coefficient for the j-th pollutant emitted from i-th building material (dimensionless)
L_i	thickness of the i-th building material (m)
M	formaldehyde emission rate from building materials ($\mu g \cdot h^{-1}$)
$\dot{M}_j^b(t)$	the hourly emission rate of the j-th pollutant from all the building materials at time t ($\mu g \cdot h^{-1}$)
MW_f	molecular weight of formaldehyde ($g \cdot mol^{-1}$)
MW_{ozone}	molecular weight of ozone ($g \cdot mol^{-1}$)
n	summation index (dimensionless)
N	ventilation rate of the room (h^{-1})
N_b	pre-determined required ventilation rate for diluting building material emissions (h^{-1})
N_c	revised required ventilation rate based on chemical reactions (h^{-1})
N_d	revised required ventilation rate based on pollutant distribution effectiveness (h^{-1})
N_i	revised required ventilation rate for intermittent ventilation (h^{-1})
N_j	required ventilation rate for the j-th VOC (h^{-1})
N_q	revised required ventilation rate based on outdoor air quality (h^{-1})
N_r	revised required ventilation rate for recirculated ventilation (h^{-1})
N_T	revised required ventilation rate for temperature variation (h^{-1})
P	formaldehyde production rate ($\mu g \cdot h^{-1}$), which is defined as $P = y_{ozone}^o v_d y_d A_d \left(\frac{MW_f}{MW_{ozone}}\right)$
P_z	number of people in the ventilation zone (person)
q_n	eigenvalues in Eq. (4) (m^{-1})
Q	airflow rate of the room ($m^3 \cdot h^{-1}$)
R	The ratio of total flow rate to the original ventilation rate (dimensionless)
R_a	ventilation rate required per unit area ($L \cdot s^{-1} \cdot m^{-2}$)
R_{bz}	the breathing zone ventilation rate ($L \cdot s^{-1}$)
R_p	ventilation rate required per person ($L \cdot s^{-1} \cdot person^{-1}$)
S_j	total counts of the j-th pollutants that determines ventilation rate (dimensionless)
S_{total}	total combinations of the material/reference pair (dimensionless)
T	temperature (K)
$t_{A,n}$	duration of the n-th non-ventilation period in intermittent ventilation (h)
$t_{B,n}$	duration of the n-th ventilation period in intermittent ventilation (h)
v_d	ozone deposition velocity ($m \cdot h^{-1}$)
V	room volume (m^3)
V_{bz}	volume of the breathing zone (m^3)
$V_{bz,x}$	volume of the x-th tiny space in the breathing zone (m^3)
X	correction factor of temperature effect on emission rate of chemical pollutant in building materials (dimensionless)
X_{lead}	correction factor of temperature effect on emission rate of the known leading pollutant (dimensionless)
y	pollutant concentration limit in indoor air quality reference ($\mu g \cdot m^{-3}$)
$y_{bz,x}$	gas-phase concentration for the j-th pollutant in the x-th tiny space of the breathing zone ($\mu g \cdot m^{-3}$)
$\overline{y}_{B,n}$	average gas-phase pollutant concentration of the n-th ventilation period in intermittent ventilation ($\mu g \cdot m^{-3}$)
y_d	formaldehyde yield (dimensionless)
$y_j(t)$	gas-phase concentration for the j-th pollutant at time t ($\mu g \cdot m^{-3}$)
$\overline{y}_{j,bz}$	average pollutant concentration within the breathing zone ($\mu g \cdot m^{-3}$)
$\overline{y}'_{j,bz}$	average pollutant concentration within the breathing zone with the revised ventilation rate ($\mu g \cdot m^{-3}$)
$y_{j,pred}$	theoretical steady-state gas-phase concentration for the j-th pollutant ($\mu g \cdot m^{-3}$)
y_{ozone}^o	outdoor ozone concentration ($\mu g \cdot m^{-3}$)

Abbreviations

ACH	air change rate per hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	computational fluid dynamics
HVAC	heating, ventilation and air conditioning
IAQ	indoor air quality
VOC	volatile organic compound
TVOC	total volatile organic compounds

Greeks

α	the ratio of pollutant concentration in outdoor air (supply air) to the concentration limit in indoor air quality reference (dimensionless)
η	outdoor air fraction in the supply air (fractional)