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BUILDING PERFORMANCE EVALUATION FOR INDOOR AIR QUALITY USING OCCUPANT CONTAMINANT INHALATION AND ATTRIBUTION TO CONTAMINANT SOURCES

Yuichi Takemasa[1,2] and Alfred Moser[1]

[1] Swiss Federal Institute of Technology Zurich, SWITZERLAND

[2] Kajima Technical Research Institute, JAPAN

Air & Climate, ETH Zentrum, LOWC5, CH-8092, Zurich, SWITZERLAND
Tel: +41 1 632 69 15 Fax: +41 1 632 10 23 E-mail: takemasa@hbt.arch.ethz.ch

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Yuichi Takemasa [1,2]
Alfred Moser [1]

[1]Swiss Federal Institute of Technology Zurich, Switzerland
[2]Kajima Technical Research Institute, Japan

Air & Climate, ETH Zentrum, LOW C5, CH-8092 Zurich, Switzerland
Tel: +41 1 632 69 15 Fax: +41 1 632 10 23 e-mail: takemasa@hbt.arch.ethz.ch

SYNOPSIS

The emissions of building materials like volatile organic compounds and indoor airborne contaminants such as environmental tobacco smoke expose occupants to hazardous substances. Although impacts of indoor air quality problems on human health, comfort, and productivity are quite large, no adequate evaluation methodology exists to assess contaminant source control techniques and building equipment systems. Even if instant indoor concentrations of many contaminants are not always high, continuous exposures to these contaminants may cause severe problems such as manifested by the sick building syndrome.

This paper proposes a method for evaluating long-term building performance in terms of indoor air quality. The approach applies exposure assessment but focuses on building performance. It employs the concept of using the total amount of substance inhaled by persons who occupy the room. This indicator is expressed by kilograms of each contaminant inhaled by persons ever present in the building during its operational life. The values include the effects of occupant rates. Concrete procedures for deriving variations of the indicators for both gaseous and particulate contaminants are described in detail. Another concept of contribution rates of contaminant sources is introduced both for instant values and on the inhalation basis. Evaluation examples of these indicators for a simple office geometry are shown for particulate matter, carbon dioxide, and formaldehyde. The results of the case studies strongly suggest the importance of indoor material selection and ventilation strategies. The contribution rate of contaminant sources makes it easier to plan a remedy for bad indoor air quality. The applicability of these indicators and future research requirements are also discussed.

LIST OF SYMBOLS

IAQ	: Indoor Air Quality
VOC	: Volatile Organic Compound
TVOC	: Total Volatile Organic Compounds
HCHO	: Formaldehyde
SBS	: Sick Building Syndrome
OCI	: Occupant airborne Contaminant Inhalation in specific spaces in absolute values
HVAC	: Heating, Ventilation, and Air-Conditioning
OCIOC	: Occupant airborne Contaminant Inhalation relative to Outside Concentration
OCIT	: Occupant airborne Contaminant Inhalation above Thresholds
SVE	: Scale for Ventilation Efficiency
CRI	: Contribution Rate for Indoor climate
CRCS	: Contribution Rate of Contaminant Sources
CFD	: Computational Fluid Dynamics
RC	: Reinforced Concrete
LCA	: Life Cycle Assessment

1. INTRODUCTION

The emissions of building materials like volatile organic compounds (VOCs) and indoor airborne contaminant such as environmental tobacco smoke expose occupants to hazardous substances. Although impacts of indoor air quality (IAQ) problems on human health, comfort, and productivity are quite large, no adequate evaluation methodology exists to assess contaminant source control techniques and building equipment systems. The potential health risk and possible injury to persons due to poor building quality must be quantitatively evaluated.

There are many indoor airborne contaminants that have impacts on human health, comfort, and productivity. A European research group has chosen 50 chemical substances as harmful inside the room [1]. Contaminants not only generated by occupants but also emitted from furniture, building materials, mechanical ventilation systems, or ducts may have strong adverse effects [2, 3]. Examples of the latter are formaldehyde (HCHO) or VOCs from building materials or furniture. Recent requirements for tighter buildings seeking energy conservation have unveiled the importance of these new IAQ problems [4]. The Healthy Residence Research Committee in Japan has recently designated 6 kinds of VOCs as harmful substances that should be urgently tackled; HCHO, toluene, xylene, wood preservatives, plastic softeners, and insecticides against white ants [5]. These tendencies support the importance of building performance evaluation in terms of IAQ.

Some airborne contaminants lead to injury in a very short time, while others have log-term adverse impacts on occupants. Even if instant indoor concentrations of many above-mentioned contaminants are not always high, continuous exposure to these contaminants may cause severe problems such as manifested by the sick building syndrome (SBS) [6]. Many health effects are not related to single exposures triggering an acute response, but are chronic, and induced either by bioaccumulation of a toxicant reaching a critical level in the target organ or tissue, or by repeated exposure causing acute episodes that ultimately lead to a chronic response [7]. Most reported TVOC concentrations in non-industrial environments are, for example, below 1 mg/m^3 and few exceed 25 mg/m^3, and at these concentration levels only sensory effects are likely to occur, but other health effects can not be excluded after long-term exposure [8]. Such investigations suggest the needs for long-term assessment indicators of IAQ.

In physiological, epidemiological, and medical science fields, peak concentration assessment is used for contaminants with acute effects, but exposure assessment is the state-of-the-art method for assessing human health risk in case of contaminants with chronic effects [9]. There are also some attempts to apply this methodology to building products. A European collaborative action for IAQ and its impact on man introduces exposure assessment after 24 hours, 3 days, and 28 days of test chamber experiments in order to evaluate adverse effects of VOC emission from solid flooring materials on occupants [7]. Taking into account this situation and the fact that more than 90% of time is spent inside buildings by people in industrial countries [10], it would be reasonable to use exposure assessment in terms of IAQ from a point of view of building performance.

The objective of this paper is to propose an approach for evaluating long-term impacts of indoor airborne contaminants on occupants, focusing mainly on performances of a particular building. This approach employs a concept of using the total amount of airborne contaminant inhaled by persons who occupy the room. Concrete procedures for deriving variations of the indicators for both gaseous and particulate contaminants are described in detail. Another concept of contribution rates of contaminant sources is introduced both for instant values and on the inhalation basis. Evaluation examples of these indicators for a simple office geometry are shown for particulate matter, carbon dioxide, and HCHO. The applicability of these indicators and future research requirements are also discussed.

2. OCCUPANT AIRBORNE CONTAMINANT INHALATION

A proposed indicator, *Occupant airborne Contaminant Inhalation in specific spaces (OCI)*, is expressed by kilograms of each contaminant inhaled by persons ever present in the building during its operational life. Allergies and eye, skin, and mucous irritations are not separately accounted for at this stage. The model does not include psychological injury, perception of comfort, nor noise, illumination, and visual stress. The following are the procedures for deriving OCI *for gaseous contaminants.* The procedures *for particulate matter* are almost the same as for gaseous contaminants and are described in *APPENDIX 1.*

Occupant Airborne Contaminant Inhalation in Absolute Values (OCI)

When the perfect diffusion of the contaminant can be assumed, the concentration of each contaminant inside the room is estimated by the following differential equation:

$$V \cdot dC = W \cdot dt - Q \cdot (C - C_0) \cdot dt \qquad (1)$$

where

- V : Volume of the room [m^3]
- W : Contaminant generation or sink [m^3 / h]
- t : Time [h]
- C_0 : Outside concentration (volumetric) [-]
- C : Concentration inside the room (volumetric) [-]
- Q : Exchanged outside air volume [m^3 / h]

Outside air volume Q is attributed to mechanical ventilation, natural ventilation, and infiltration through cracks. The contaminant generation rate W can be written as:

$$W = W_h + \sum_i W_w(i) + W_f + W_{eq} + W_o \qquad (2)$$

where

- W_h : Contaminant generation from occupants [m^3 / h]
- $W_w(i)$: Contaminant generation or sink from wall surfaces made of the material i [m^3 / h]
- W_f : Contaminant generation or sink from furniture and electrical equipment [m^3 / h]
- W_{eq} : Contaminant generation or sink from HVAC and combustion systems [m^3 / h]
- W_o : Contaminant generation or sink from other sources [m^3 / h]

Here, contaminant generation is expressed by positive values, while contaminant sink is shown by negative values. There are many kinds of contaminant generation and sink. They are caused by building materials, poor maintenance, and inappropriate operation of the building. Examples for source mechanisms are emission or release of mass, evaporation, desorption, resuspension, growth of micro-organisms, and radio activity, and the most important sink mechanisms are deposition (absorption and adsorption), sedimentation, plate out, filtering, condensation, chemical reaction, and radio active decay [11]. W_{eq} in the equation (2) includes all the effects concerning Heating, Ventilating, and Air-Conditioning (HVAC) systems such as ducts, fans, heat exchangers, filters, and humidifiers, and other processes such as combustion. The last term W_o includes the other sources such as contaminants generated by smoking or microbiological organisms.

Here, we will try to propose an approach for evaluating long-term building performance in terms of IAQ. The approach is the concept using the total amount of contaminant inhaled by persons who occupy the room. In this paper, we name it *Occupant airborne Contaminant Inhalation in specific spaces in absolute values (OCI)*. The OCI value is derived by the following procedures for each contaminant. The instant amount of the inhaled contaminant is expressed as:

$$M_{ci} = k \cdot f_{res} \cdot V_{br} \cdot C \qquad (3)$$

where

- M_{ci} : Instant amount of contaminant inhaled by occupants [g / (h·person)]
- k : Coefficient for providing the amount of each contaminant per unit volume [g / m^3]
- f_{res} : Respiratory frequency [1 / h]
- V_{br} : Breathing air volume per one respiration per person [m^3 / person]

Here, M_{ci} is an instant value and a function of time. f_{res} and V_{br} are also functions of time because they depend on the level of human activities [12]. The coefficient k is an order of density and can be drawn from the gas law if the assumption of the perfect gas is appropriate *(APPENDIX 2).*

If the equation (3) is multiplied by a weighting factor, w_{oc}, representing occupancy in the room and integrated in terms of time, we can obtain an absolute OCI value during the period concerned (hour, day, week, month, year, or even building lifetime). Here, w_{oc} is a function of time.

$$OCI = \int M_{ci} \cdot w_{oc} \cdot dt \qquad (4)$$

where

OCI : Total amount of contaminant inhaled by occupants during the period concerned [g] (Occupant Contaminant Inhalation in absolute values)
w_{oc} : Weighting factor for occupancy [person]

OCI means the total amount of contaminant inhaled by occupants in a specific indoor space, including the effects of occupant rate of the room. This means that OCI equals zero if the room is always vacant and the occupant rate is zero, and that the indicators of two rooms should be equal if one person lives in a larger room but gets the same dose as another person living in a smaller room. OCI can be thought to be a measure of the total hazards caused by IAQ problems in the building. OCI has a dimension of the number of occupants in the room times potential dose, which is normally used in physiology [9].

If we divide the resultant value by the number of regular occupancy, a normalized value for contaminants inhaled by occupants can be obtained. The obtained value means an average amount of contaminant inhaled by one person during the time concerned. It is similar to the above-mentioned potential dose.

$$OCI_{norm} = OCI / N_{ro} \qquad (5)$$

where

OCI_{norm} : Normalized OCI value during the period concerned [g / person]
N_{ro} : Number of nominal occupancy [person]

If we focus only on the average inhaled values during the occupant time, the average amount of contaminant per one hour and one person inhaled only by the people who actually occupy the room during the period concerned can be used. Substantial effects only during the occupant period are considered by this value.

$$OCI_{ave} = OCI / \int w_{oc} \cdot dt \qquad (6)$$

where

OCI_{ave} : Average amount of OCI per hour and person related only to the people who actually occupy the room during the summed occupied period [g /(hour·person)]

This value is useful with relatively slight variations in the contaminant concentrations. When there is a sharp peak in contaminant concentration or when only an acute adverse effect on human health is expected, peak values for contaminant concentrations should be used.

Occupant Airborne Contaminant Inhalation relative to Outside Concentration (OCIOC)

When the contaminant exists in nature and the indoor contaminant concentration is always higher than the outside concentration, another concept of *Occupant airborne Contaminant Inhalation relative to Outside Concentration (OCIOC)* can be more effective. The following equation can be used in place of the equation (3):

$$M_{ci} = k \cdot f_{res} \cdot V_{br} \cdot (C - C_0) \qquad (7)$$

In this equation, we subtract the outside concentration rate C_0 from the indoor concentration rate C in order to neglect the effects of contaminants contained in the outside air. This value makes it possible to concentrate only on the impacts of contaminants generated inside the building. Various values for inhaled substance such as OCIOC, $OCIOC_{norm}$, $OCIOC_{ave}$ can be calculated by the same procedures described in the previous section (equations (4) to (6)). Note again that M_{ci} in this equation should be basically positive.

The OCIOC values are useful when outside air pollution is unavoidable but indoor contaminant generation is the central problem that should be solved. These values may represent building performances in terms of IAQ.

Occupant Airborne Contaminant Inhalation above Thresholds (OCIT)

For some substances, there are thresholds below which contaminant inhalation is not perceived by occupants or does not cause any substantial problems. Bioeffluent and CO_2 concentration under 1,000 ppm would be such examples.

In such a case, we can introduce a different version of *Occupant airborne Contaminant Inhalation above Thresholds (OCIT)*. It is interpreted as the amount of contaminant that exceeds the threshold value and is inhaled by occupants. This concept can be useful when adverse effects of the substance on occupants are negligible at smaller values below the thresholds. This concept makes it possible to quantitatively evaluate the occupants' exposure level over contaminant thresholds during the time concerned.

In order to calculate this value, the equation (3) should be replaced by the following equations:

$$M_{ci} = k \cdot f_{res} \cdot V_{br} \cdot (C - C_{th}) \qquad \text{when } C > C_{th}$$
$$M_{ci} = 0 \qquad \text{when } C \leq C_{th} \qquad (8)$$

where

C_{th} : Threshold value for the gaseous contaminant [-]

Various values for inhaled substance such as OCIT, $OCIT_{norm}$, $OCIT_{ave}$ can be calculated by the same procedures described in the previous sections (equations (4) to (6)). We should note that these values refer not to perceived stress levels but to exposure levels of concentrations that exceed thresholds. Perceived stress is a very strong nonlinear system and is affected also by factors other than contaminant concentrations such as social factors, noise, the thermal and illumination environments, etc. Furthermore, there are many contaminants whose thresholds have not been established in non-industrial indoor air [8].

3. CONTRIBUTION RATE OF CONTAMINANT SOURCES (CRCS)

In the previous sections, various concepts of Occupant Contaminant Inhalation (OCI) are introduced in order to evaluate IAQ conditions using exposure assessment. Here, we introduce another concept of *Contribution Rate of Contaminant Sources (CRCS).*

The concept of CRCS is based on the idea of assessing the contribution of individual contaminant sources to indoor contaminant concentrations and OCI values. This idea makes use of the linearity of the governing equations for indoor airborne contaminant transportation, although this assumption is not valid for active contaminants. According to these useful characteristics, we can understand quantitatively the contributions of particular contaminant sources to IAQ deterioration. Therefore CRCS has a potential to make it easier to plan efficient source control methods. CRCS can also be used to evaluate the influences of non-uniform concentration distributions.

The same kinds of approaches as described here have been introduced for scale-model tracer gas tests of a large sports arena as contribution rates of each duct line to the air conditioning of each zone [13]. These values were used to design the optimal control system for room air temperatures. Making efficient use of Computational Fluid Dynamics (CFD), practical indicators were introduced for the evaluation of ventilation efficiency inside the room

(SVE: Scale for Ventilation Efficiency) [14] and the mechanisms of indoor thermal environment (CRI: Contribution Rate for Indoor climate) [15].

The following are procedures for deriving CRCS both for instant values and on the inhalation basis.

Contribution Rate of Contaminant Sources for Instant Values ($CRCS_{inst}$)

Contribution Rate of Contaminant Sources for instant values ($CRCS_{inst}$) for gaseous contaminants can be calculated by the following equation:

$$CRCS_{inst}(j) = C_p(j) / C \tag{9}$$

where

$CRCS_{inst}(j)$: Contribution rate of contaminant source j for instant values [-]

$C_p(j)$: Partial concentration due to contaminant source j [-]

$C_p(j)$ is calculated by steady-state equations for a given contaminant source. According to the linearity of the governing equation for concentrations, the following conditions are automatically satisfied.

$$\sum_j C_p(j) = C \quad \text{and hence} \quad \sum_j CRCS_{inst}(j) = 1.0 \tag{10}$$

Instant contribution rates of contaminant sources can be calculated not only with assumptions of perfect mixing but also when non-uniform concentration distributions are taken into account by CFD. The outside concentration can also be treated as one of the contaminant sources. $CRCS_{inst}$ can be applied to contaminant sink such as deposition or absorption by incorporating negative values. $CRCS_{inst}$ is useful to plan a remedy against *acute* effects from contaminant sources. Deriving procedures for particulate matter are similar.

Contribution Rate of Contaminant Sources on the Inhalation Basis ($CRCS_{ib}$)

Contribution Rate of Contaminant Sources on the inhalation basis ($CRCS_{ib}$) for gaseous contaminants can be calculated by the following equations:

$$CRCS_{ib}(j) = \int M_{cip}(j) \cdot w_{oc} \cdot dt / OCI \tag{11}$$

$$M_{cip}(j) = k \cdot f_{res} \cdot V_{br} \cdot C_p(j) \tag{12}$$

where

$CRCS_{ib}(j)$: Contribution rate of contaminant source j on the inhalation basis [-]

$M_{cip}(j)$: Amount of substance emitted by contaminant source j and inhaled by occupants [g / (h·person)] (for particulate matter, see *APPENDIX 1*)

When perfect mixing in the space is not assumed or there is time dependency of material emissions, $CRCS_{ib}(j)$ values are different from $CRCS_{inst}(j)$. The total value for $CRCS_{ib}$ is 1.0 as in the equation (10). $CRCS_{ib}$ is useful to plan a remedy against *chronic* effects from contaminant sources.

4. CASE STUDIES

Some case studies are conducted for a simple office geometry focusing on inhaled contaminants (OCI) under the conditions summarized in Table 1. Particulate matter, carbon dioxide (CO_2), and HCHO are selected as indoor airborne contaminants for OCI evaluations. HCHO is also used for CRCS evaluations. More complicated examples are left for the future.

Occupant Contaminant Inhalation relative to Outside Concentration (OCIOC)

Figure 1 shows estimated inhaled particulate matter relative to the outside concentration per one year and one person ($OCIOC_{norm}$) as a function of an air change rate and an average occupant rate. The average occupant rate is an averaged value between 8:00 and 18:00 on week days excluding the time between 12:00 and 13:00 (Table 1). Here, it is assumed that an instant occupant rate is always 0 or 100% (0 or 2 occupants) even if an average occupant rate over time is neither 0 nor 100%. This condition is selected in order to evaluate the largest OCIOC values for each average occupant rate. The inhaled particulate matter per person becomes smaller as the occupant rate becomes smaller because of the shorter occupancy time. The $OCIOC_{norm}$ values are proportional to the average occupant rate, because contaminant concentration is the same during the occupancy period. The $OCIOC_{norm}$ values are inversely-proportional to the air change rate and decrease as the air change rate increases. The $OCIOC_{norm}$ value is about 135 mg/(year·person) when the air change rate is a normal value of 2 h^{-1} and the average occupant rate is 100%. The data for particulate diameters are required to evaluate the particulate matter absorbed by the human body, because the absorption rate is dependent on the diameters.

Table 1 Calculation conditions.

- Room size: 4 m by 6 m by 3 m [H]. Room air temperature: 24 °C.
- Occupancy time: 8:00 to 18:00 including a break from 12:00 to 13:00. 2 occupants.
- Saturday and Sunday are holidays, but it is assumed that there are no national holidays.
- Generation rate of particular matter: 8.45 mg/(h·person) [16]. A value for total particular matter (TPM) is used. A pulmonary ventilation volume is dependent on the metabolic heat production rate and is estimated to be 0.49 m^3/(h·person) at desk work according to [17].
- Generation of CO_2: 200 ml/(min·person) [18].
- Generation of HCHO is assumed to be constant as follows [19].
  50 books: 1.1 μg/(h·book), 2 pairs of shoes: 1.6 μg/(h·pair), Ceiling material: 0.3 μg/(100cm^2·h)
  Office carpet: 0.2 μg/(100cm^2·h), Reinforced concrete : Assumed to be 0, Particle boards: 8.3 μg/(100cm^2·h)
  Plywood: 18.0 μg/(100cm^2·h)

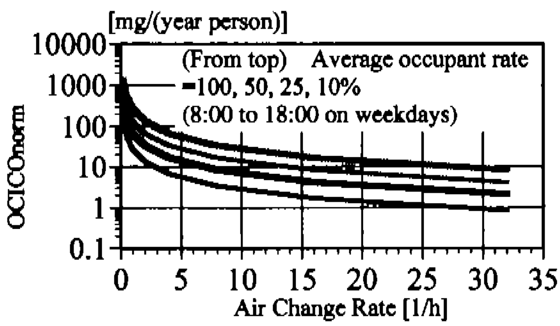


Figure 1 Estimated $OCIOC_{norm}$ values for particulate matter.

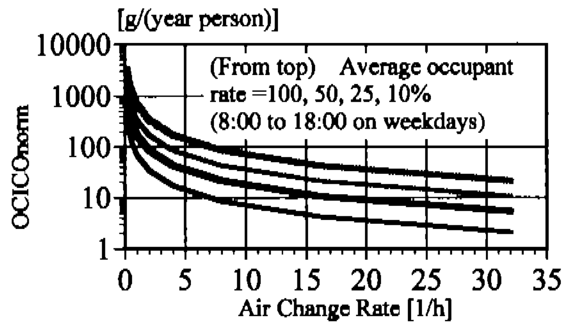


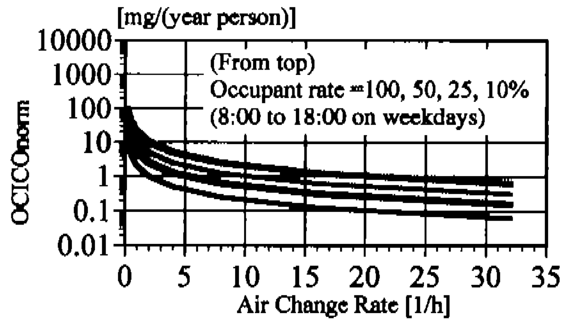
Figure 2 Estimated $OCIOC_{norm}$ values for CO_2.

Figure 2 shows estimated $OCIOC_{norm}$ values for CO_2 per one year. It depends on the air change rate and the average occupant rate in the same manner as the particulate matter. The $OCIOC_{norm}$ value for CO_2 is about 345 g/(year·person) with an air change rate of 2 h^{-1} and an occupant rate of 100%. Although the inhalation of CO_2 is not directly hazardous to human health unless it exceeds a certain level (for example 5000 ppm), this value can be an IAQ indicator for a certain period including the effect of occupant rates.

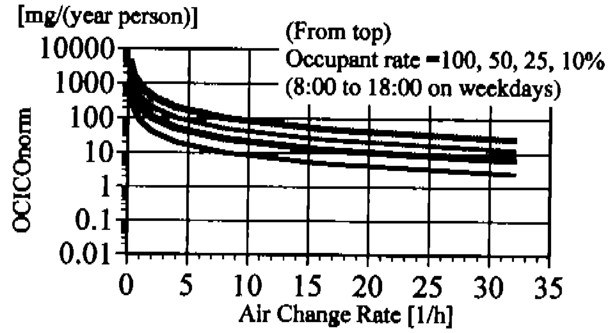
Figure 3 illustrates estimated $OCIOC_{norm}$ values for HCHO per one year. In this figure, the influences of the selection of wall materials are investigated. Three materials for side walls, reinforced concrete (RC), particle boards, and plywood are compared. The occupant rate can be interpreted also as a constant value during the whole office hours in this study. Note that the HCHO emission rate is assumed to be constant during the whole year, which is not precise because of the neglect of the emission rate reduction as time proceeds. In case of RC, the $OCIOC_{norm}$ values for HCHO are small, for example 10 mg/(year·person) with an air change rate of 2 h^{-1} and an occupant rate of 100%. This is due to the assumption of no emission on the RC walls (Table 1). However, the $OCIOC_{norm}$ values for HCHO are very high in case of particle boards with a value of about 400 mg/(year·person) in the same condition. The values for plywood are higher than that, for example about 870 mg/(year·person) under the same condition. This is almost 90 times larger than the value with RC. This result strongly suggests the importance of the indoor material selection process.

Contribution Rate for Contaminant Sources (CRCS)

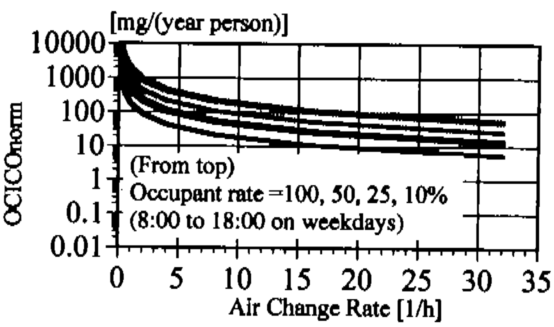
Figure 4 shows CRCS values of each contaminant source with different area ratios of particle boards against RC for side walls. The contaminant is HCHO. The influence of the outside concentration is neglected in this study. In this evaluation, CRCS values for instant values and on the inhalation basis are the same because perfect mixing in the air and constant contaminant sources are assumed in the room. One can see high CRCS values from side walls when the area ratio of particle boards is high. The CRCS value from side walls becomes comparable with the other sources only when more than 31/32 or 97% of the side walls made of particle boards are replaced by RC walls. This means that a drastic change of side wall material into one with less HCHO emission can be an effective remedy against high HCHO concentration but that only a small replacement does not work very well. The CRCS value in side walls becomes zero if RC walls are fully installed. As described here, CRCS can be used to evaluate the effects of source control methods.



(a) Reinforced concrete



(b) Particle boards



(c) Plywood

Figure 3 OCIOC$_{norm}$ *values for HCHO with side walls made of various materials.*

5. DISCUSSION

Some possible indicators for building performances in terms of IAQ, Occupant Contaminant Inhalation (OCI) and Contribution Rate of Contaminant Sources (CRCS), were introduced, and simple case studies using them were described. There are many things that should be done in the future. The following are discussions on the advantages and limitations of these indicators and required future research.

Advantages

1. The concept of OCI makes it possible to assess long-term effects of indoor contaminants on occupants. This characteristic is suitable for the conditions where the instant contaminant concentration is not high, but continuous contaminant inhalation is a main cause of chronic adverse effects. This is also effective when indoor airborne contaminant concentration is strongly time-dependent, e.g., VOC emissions from wall materials.
2. OCI has a potential to be practically used when more knowledge becomes available

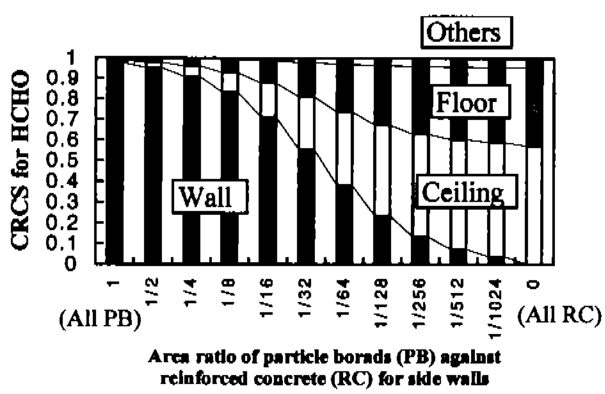


Figure 4 CRCS values of each contaminant source with different area ratios of particle boards against reinforced concrete for side walls. (Effects of outside concentration are neglected.)

on dose-response relationship investigations in physiological and medical fields.

3. OCI includes the effects of occupant rates. This means that OCI values show building performances on IAQ from the occupants' point of view and with respect to health impact.
4. Life Cycle Assessment (LCA) is useful for the evaluation of building sustainability in terms of energy consumption, CO_2 emissions, or acidification factors [20]. As IAQ is also an important factor together with the aforementioned [21], it is reasonable to employ long-term assessment indicators for IAQ such as OCI.
5. CRCS values help us analyze the mechanisms of contaminant transportation inside the room. They also make it easier to plan an efficient source control remedy for IAQ problems. Not only instant but also long-term evaluations become possible by combining the concepts of CRCS with those of OCI ($CRCS_{ib}$).

Limitations

1. Methods for evaluating indoor contaminant concentrations have not been fully established. There still remain many phenomena that cannot be modeled precisely such as emission processes from building materials and their interactions with thermal conditions.
2. It is not today possible to conclude that sensory irritation is associated with the sum of mass concentration of contaminants such as VOCs at the low exposure levels typically encountered in non-industrial indoor air.
3. Exposure-response relationships in IAQ problems have not been established yet. Further research in hygiene and physiology fields is essential to overcome this difficult question.
4. OCI values do not evaluate short-term effects on human health. Peak concentration assessment is necessary for acute effects of indoor airborne contaminants. It should be clarified for which contaminants the long-term assessment is efficient.
5. OCI assumes that the contaminants act only through respiration. This assumption may not be reasonable for the other symptoms such as eye irritations or skin dryness.
6. It is sometimes difficult to predict occupant rates appropriately during the design stage. However, this is unavoidable when one evaluates spaces from occupants' point of view.
7. It is difficult to validate OCI values by field measurements. One should use values for contaminant concentrations for this purpose.
8. CRCS proposed in this paper can be applied only to passive contaminants.

Further Research Requirement

Considering the above factors, it is suitable to evaluate IAQ by the long-term assessment or indoor contaminant concentrations, depending on the contaminant. There are still strong demands for further research concerning the following points.

1. Emission processes of indoor contaminants from building materials are affected by such factors as temperatures, air velocities, and contaminant concentrations. Emission mechanisms from building materials should be included in environmental evaluation models.
2. Indoor air quality has strong relevance to or sometimes trade-offs with other factors such as energy consumption, thermal comfort, and the light environment. Therefore, a prediction model that can simultaneously treat various factors is desired to realize sustainable buildings. The model should be able to evaluate effects of natural ventilation or thermal storage capacity of buildings, taking unsteady-state phenomena into account.
3. In this paper, indoor airborne contaminant concentration has been assumed to be uniform in a room. When this uniformity is not appropriate, for example in case of displacement ventilation, other sophisticated methods such as CFD or chamber tests should be made to estimate indoor contaminant concentrations properly [10]. However, the concepts described in this paper are also applicable to such cases. Values for ventilation efficiency obtained by CFD or chamber tests can be effectively used in the unsteady-state simulation described above to make more reasonable and precise evaluations possible.
4. Inhalation must be placed in the context of total exposure assessment, which requires consideration of all pertinent environmental media and all routes of entry into the body.

6. ACKNOWLEDGMENT

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APPENDIX 1 Occupant Contaminant Inhalation (OCI) in Case of Particulate Matter

When the contaminant concerned is particulate matter, a procedure for estimating inhaled substance is a little different from the case of gaseous contaminants. If the perfect diffusion of the contaminant can be assumed, the contaminant concentration inside the room is expressed by the following differential equation:

$$V \cdot dC' = W' \cdot dt - Q \cdot (C' - C'_0) \cdot dt \qquad \text{(A1-1)}$$

where the superscript ' means values not for gaseous contaminants but for particulate matter.

W' : Contaminant generation [g / h]
C'_0 : Outside concentration rate [g / m^3]
C' : Concentration rate inside the room [g / m^3]

The instant substance inhaled by occupants is expressed by the next equations for the equations (3), (7), (8), and (12) respectively:

$$M_{ci} = f_{res} \cdot V_{br} \cdot C' \qquad \text{(A1-2)}$$
$$M_{ci} = f_{res} \cdot V_{br} \cdot (C' - C'_0) \qquad \text{(A1-3)}$$
$$M_{ci} = f_{res} \cdot V_{br} \cdot (C' - C'_{th}) \text{ when } C' > C'_{th} \text{ and } = 0 \text{ when } C' \le C'_{th} \qquad \text{(A1-4)}$$
$$M_{ci}(j) = f_{res} \cdot V_{br} \cdot C'_p(j) \qquad \text{(A1-5)}$$

where

C'_{th} : Threshold value for particulate matter [g / m^3]
$C'_p(j)$: Partial concentration for a contaminant source j for particulate matter [g / m^3]

Note that there is no coefficient k in the equations (A1-2) to (A1-5) as in the equation (3). Various parameters for OCI are calculated in the same way as shown in the previous explanation for gaseous contaminants.

The above-mentioned procedure can also be used to derive values for gaseous contaminants and compound mixtures usually expressed by mass concentrations, e.g., TVOC [8].

APPENDIX 2 Calculation of Coefficient k in Equation (3)

The coefficient k in the equation (3) for each gaseous contaminant can be given by the following equation, if the contaminant can be assumed to be a perfect gas:

$$k = (M \cdot P) / (R \cdot T) \qquad \text{(A2-1)}$$

where

M : Molecular weight of each gaseous contaminant [g / mol]
P : Indoor pressure [Pa]
R : Gas constant [J / (mol·K)] (= 8.3145)
T : Absolute indoor air temperature [K]

For a compound mixture, one should calculate a total k value, from the constitution of the mixture and the equation (A2-1).