COMPARISON OF MECHANICAL AND NATURAL VENTILATION USING LONG-TERM EVALUATION MODEL FOR INDOOR AIR QUALITY, THERMAL ENVIRONMENT, AND ENERGY CONSUMPTION

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ABSTRACT

There are often tradeoffs among improving IAQ (Indoor Air Quality), maintaining the thermal comfort, and reducing energy consumption for HVAC (Heating, Ventilating, and Air-Conditioning) systems. A prediction model that can simultaneously treat these factors is required to realize good design of sustainable buildings. For this paper, a concept of *Occupant Contaminant Inhalation* is used for long-term assessment of IAQ. A long-term evaluation indicator for other factors such as air temperature is also introduced (*Occupancy-weighted Accumulated Deviation from thresholds*). The paper also describes a long-term simulation model for evaluating IAQ, the thermal environment, and energy consumption. The model takes vertical temperature distribution within rooms and unsteady phenomena due to the thermal storage capacity of buildings into account. Case studies are made using this model to compare the performance of mechanical and natural ventilation in a normal office space in Tokyo. It is shown that natural ventilation is effective to reduce energy consumption for HVAC systems and to improve IAQ while maintaining the thermal comfort when ventilation strategies are appropriate. The proposed design tool will help to create buildings with low energy consumption without compromising comfort and occupant health.

INTRODUCTION

There are often tradeoffs among improving IAQ, maintaining the thermal comfort, and reducing energy consumption for HVAC systems that cause difficulties during design optimization [1]. A prediction model that can simultaneously treat these factors is required to realize good design of sustainable buildings [2, 3]. Life Cycle Assessment (LCA) is useful for evaluating the environmental impact of buildings such as energy consumption, CO_2 emission, or acidification factors [4, 5]. As the indoor environment is also important together with the aforementioned [1], it is reasonable to employ long-term assessment indicators for the indoor environment. These indicators are useful especially when natural energy is used and the indoor environment varies within a certain range.

This paper introduces long-term environmental indicators such as *Occupant Contaminant Inhalation* [6] and *Occupancy-weighted Accumulated Deviation from thresholds*. An integrated dynamic simulation model that simultaneously evaluates IAQ, the thermal environment, and energy consumption of HVAC systems is also explained. Case studies using this simulation model are made to investigate the effects of natural ventilation, mechanical ventilation, and a combination of both with a sophisticated control strategy.

OCCUPANT AIRBORNE CONTAMINANT INHALATION

Even if instant indoor concentrations of many contaminants are not always high, continuous exposure to these contaminants may cause severe problems such as manifested by the sick building syndrome (SBS) [7]. In physiological, toxicological, or medical science fields, exposure assessment is the state-of-the-art method for assessing human health risk in case of contaminants with chronic effects [8, 9]. There are also some attempts to apply this methodology to buildings. "A European Collaborative Action for IAQ and its Impact on Man" introduces exposure assessment for chamber tests to evaluate adverse effects of VOC (Volatile Organic Compound) emission from solid flooring materials [10]. IEA annex 27 (Evaluation and Demonstration of Domestic Ventilation Systems) uses the number of hours above pollutant level concentration and cumulated values above threshold limits for each occupant in residential buildings (dimensions in ppm·h) [11]. Furthermore, IAQ tends to be time-dependent when natural ventilation is utilized or the amount of contaminant emission varies dramatically over time, e.g., VOC emission from wall materials or furniture. Taking into account these situations, it is reasonable to use long-term assessment of IAQ from the viewpoint of building performance. This approach employs a concept of using the total amount of airborne contaminant inhaled by persons who occupy the room. Procedures for deriving variations of the indicators are described in the *APPENDIX* (for details, see [6]).

The proposed indicator, *Occupant airborne Contaminant Inhalation in absolute values* (we call it *OCI* here*)*, 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 membrane 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.

When the contaminant exists in outdoor air and the indoor contaminant concentration is always higher than the outside concentration, *Occupant airborne Contaminant Inhalation relative to Outside Concentration (OCIOC)* can be more effective. This is useful when outside air pollution is unavoidable but indoor contaminant generation is the central problem.

For some substances, there are thresholds below which contaminant inhalation is not perceived by occupants or does not cause any substantial problems (e.g., bioeffluent). In such a case, we can introduce *Occupant airborne Contaminant Inhalation above Thresholds (OCIT).* This is the amount of contaminant that exceeds the threshold value and is inhaled by occupants.

OCCUPANCY-WEIGHTED ACCUMULATED DEVIATION FROM THRESHOLDS

There are many kinds of perception that occupants have inside buildings in everyday life: the thermal environment, the light environment, etc. If these factors are controlled by appropriate active systems, for instance air temperatures are controlled by HVAC systems, resulting values for these remain almost constant. In such cases, we can evaluate the discomfort perceived by occupants simply by these constant values. However, when the variable varies over time according to the surrounding conditions, other methods are required to properly evaluate the varying environment. This is true for the spaces where natural ventilation is used and room air temperature varies due to the outside conditions. This is also true for illumination on desks when daylighting is utilized to conserve electric energy for artificial lighting.

Thinking about these situations, a new indicator, *Occupancy-weighted Accumulated Deviation from thresholds* (we call it *OAD* here), is introduced for various factors. This concept enables us to quantitatively evaluate total exposure levels caused by each factor during the time concerned. OAD is calculated by integrating the deviation from thresholds multiplied by occupant rates over time. The general form can be expressed by the following equations:

$$OAD_+(i) = \int dv_+(i) \cdot w_{oc} \cdot dt$$
$$OAD_-(i) = \int dv_-(i) \cdot w_{oc} \cdot dt \qquad (1)$$

$$dv_+(i) = V(i) - Vmax(i) \quad \text{when } Vmax(i) \le V(i)$$
$$dv_+(i) = 0 \quad \text{when } V(i) \le Vmax(i)$$
$$dv_-(i) = V(i) - Vmin(i) \quad \text{when } V(i) \le Vmin(i)$$
$$dv_-(i) = 0 \quad \text{when } Vmin(i) \le V(i) \qquad (2)$$

where

OAD(i) : OAD value for the variable i by all occupants [?· h· person]
('?' means a unit of "V (i)"; for example, °C for air temperature)
i : Index for each environmental factor (temperature, humidity, etc.)
\+ : Subscript meaning that the values refer to the upper discomfort range
\- : Subscript meaning that the values refer to the lower discomfort range
dv(i) : Deviation of the valuable i from the comfort range [?]
V(i) : Instant value for the variable i [?]
Vmax(i) : Upper comfort threshold for the variable i [?]
Vmin(i) : Lower comfort threshold for the variable i [?]
w_{oc} : Weighting factor for occupancy [person] (see the equation (A-2) in the APPENDIX)

V(i) can be any variable related to human perception such as air temperature, air humidity, air velocity, mean radiant temperature (MRT), operative temperature, predicted mean vote (PMV), or illumination. OAD values include the effects of occupant rates and become zero when there are no occupants all the time. There are 2 types of OAD values (OAD+ and OAD-). Stress perceived by occupants is usually not proportional to OAD values and is dependent not only on dv(i) but also health conditions of occupants, personal differences of perception, or other factors. Normalized values (OAD_{norm}) and average values (OAD_{ave}) are derived by the same procedures as OCI_{norm} and OCI_{ave} (see the *APPENDIX*).

INTEGRATED DYNAMIC SIMULATION MODEL FOR IAQ, THERMAL ENVIRONMENT, AND ENERGY CONSUMPTION FOR HVAC SYSTEMS

An integrated dynamic simulation model for evaluating IAQ, the thermal environment, and energy consumption for HVAC systems has been developed. In this model, a zonal model for predicting vertical temperature distribution in a space is used, together with models for dynamic wall heat conduction and transmitted solar radiation [12, 13, 14]. Indoor humidity and airborne contaminant concentration distributions can also be calculated. Annual simulations are possible with schedule data for internal heat, humidity, and airborne contaminant sources. HVAC control and heat transfer through various window systems can be treated [15]. Natural ventilation strategies can be investigated and long-term evaluation using OCI and OAD is included in this simulation model. The outline of the simulation tool is summarized in Figure 1.

Main Available Features

- Annual meteorological data
- Zonal model
- Calculation of paths of supply jets
- Boundary layer theory for ascending or descending currents along walls
- Evaluation of transmitted solar radiation
- Humidity transfer
- Indoor airborne contaminant transfer
- Window heat transfer model
- HVAC control
- Natural ventilation strategy
- Dynamic wall heat transmission
- Schedule data (occupants, sources, etc.)
- Long-term evaluation of indoor environment

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Main Outputs

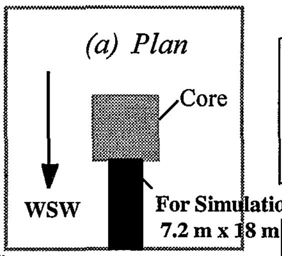
- Air temperature distribution
- Radiative thermal environment
- Air humidity distribution
- Contaminant concentration distribution
- Energy consumption for heating and cooling
- Energy consumption for fans
- Occupant Contaminant Inhalation (OCI)
- Occupancy-weighted Accumulated Deviation from thresholds (OAD)
- Control status history

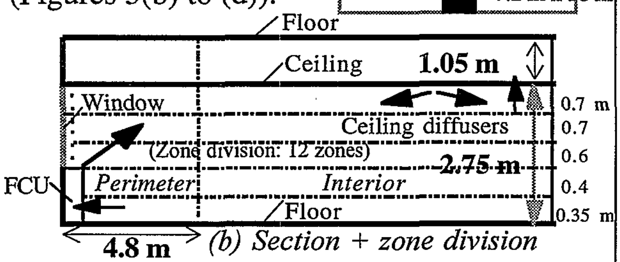
Figure 1 Outline of the integrated dynamic simulation tool for evaluating IAQ, the thermal environment, and energy consumption of HVAC systems.

CASE STUDIES

Case studies using the long-term evaluation model are made to investigate some ventilation strategies including natural ventilation and a combination of natural and mechanical systems. A part of a normal office space is chosen (see Figure 2) and the annual standard meteorological data in Tokyo is used. Table 1 shows calculation cases. Case 1 uses mechanical ventilation for the entire year. Case 2 uses natural ventilation from April to October without controls. Case 3 is the combination of mechanical and natural ventilation with sophisticated controls (4 types of maximum opening areas). Calculation conditions are shown in Table 2.

Figure 3 shows variations of mechanically removed heat, air temperature, humidity, and CO_2 concentration for two days in June. According to Figure 3(a), mechanically removed heat exists continuously for Case 1 while natural ventilation is switched to mechanical ventilation around 14:00 h and 10:30 h in Case 3. As for air temperature, humidity, and CO_2 concentration, Case 3 is more or less between Case 1 and Case 2 (Figures 3(b) to (d)).





(b) Section + zone division

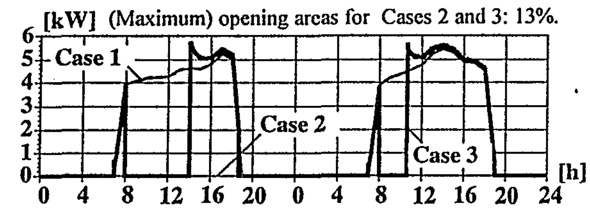
Figure 2 Outline of the example office facing west-south-west.

Table 1 Calculation cases.

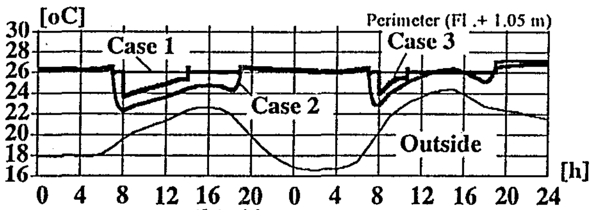
Case 1:	Mechanical Ventilation
Case 2:	Natural Ventilation without Controls (from April to October) + Mechanical Ventilation (other months)
Case 3:	Natural + Mechanical Ventilation with Controls (see Table 2)

Table 2 Calculation conditions.

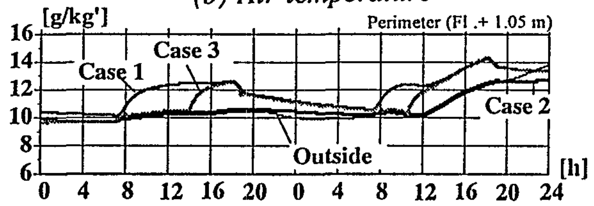
Standard meteorological data in Tokyo. Wind effects are neglected.
Natural ventilation for Case 2: from 8:00 to 18:00 on week days.
For Case 3: Maximum opening areas are 13, 7, 3, and 1.6% of facade.
When natural ventilation (NV) is more effective for 1 h--->NV start.
When room temperature is out of the comfort range for 1 h
---> NV stop. Opening area controls: PI controls by air temperature.
Occupant rate: 8:00 to 18:00 (Weekdays), 0.1 persons/m^2 (constant).
Comfort range: 22 to 26°C (air temperature). No night-time ventilation.
Target temperature: 22°C (heating), 26°C (cooling). Fan power: 750 W.
Windows: Single glass (τ=.31, a=.43) + Venetian blind (τ=.1, a=.5).
Floor: Carpet 10 + tile 10 + air + reinforced concrete (RC) 150 (mm).
Ceiling: Acoustic tile 9 + gypsum board 12 (mm).
Exterior wall: Styrene board 25 + RC 150 + tile 10 (mm).
Outside air intake: 389 m^3/h. Infiltration rate: 0.1 1/h (constant).
Heat, humidity & CO_2 generation: 58 W, 73 g/h and 12 l/h per person.
COP of HVAC systems: 3.27 (heating), 3.36 (cooling) [5].
Pulmonary ventilation volume: 0.49 m^3/(h·person) [6]. Others: [12-15].



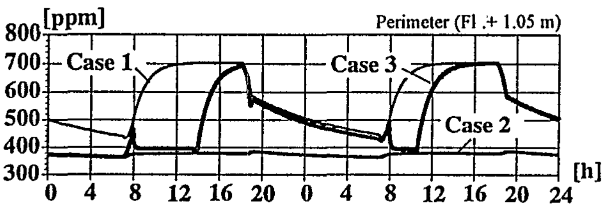
(a) Mechanically removed heat



(b) Air temperature



(c) Absolute humidity



(d) CO_2 concentration

Figure 3 Variations over time (in June).

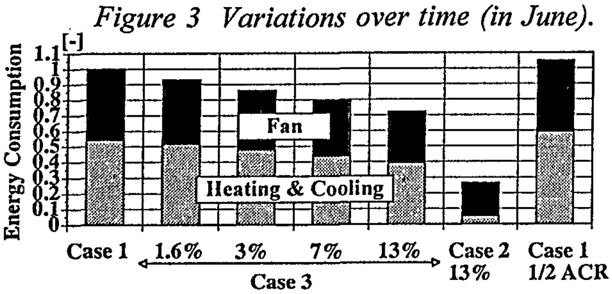


Figure 4 Energy for HVAC operation.

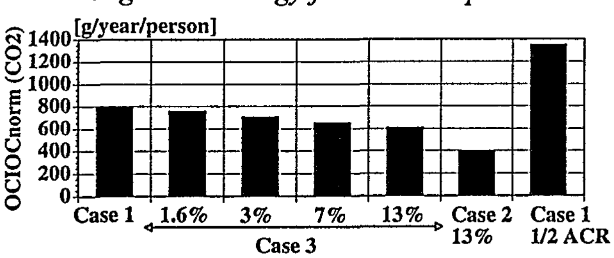


Figure 5 $OCIOC_{norm}$ values for CO_2.

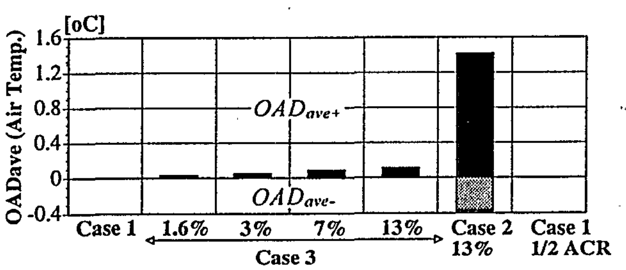
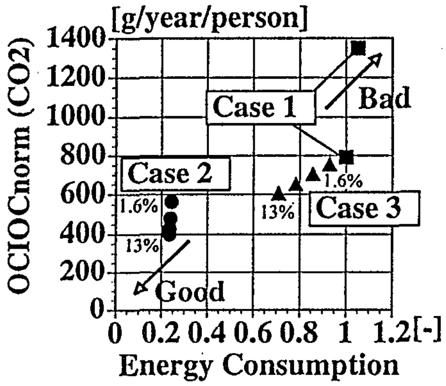
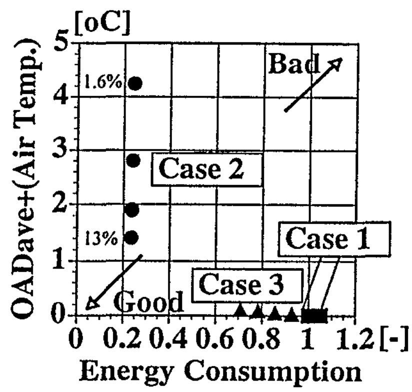


Figure 6 OAD_{ave} values for air temperature.



(a) Energy vs. IAQ



(b) Energy vs. thermal environment

Figure 7 Relation among energy consumption, IAQ, and the thermal environment.

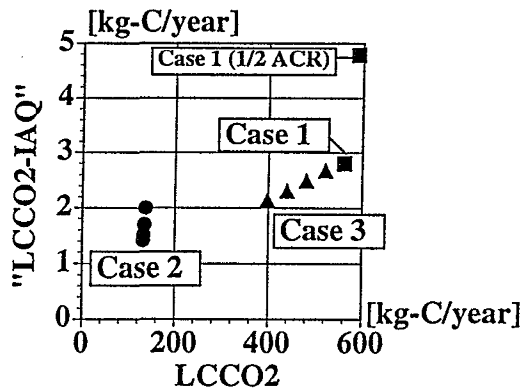


Figure 8 $LCCO_2$ emitted from HVAC systems and inhaled by occupants.

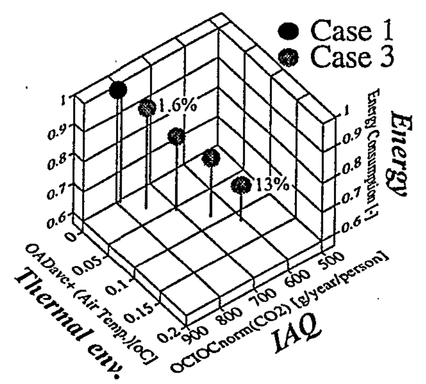


Figure 9 3-D relation among energy consumption, IAQ, and the thermal environment.

Figures 4, 5, and 6 show the results of the long-term evaluation in terms of energy consumption, IAQ, and the thermal environment, respectively.

In Figure 4, energy consumption for HVAC systems including fan power is shown on an electricity basis. The results are normalized by the value of Case 1. Energy consumption for Case 3 decreases as the maximum opening area becomes larger. When the maximum opening area is 13% of the facade, energy consumption is reduced by around 30%. Energy consumption becomes very small in case of natural ventilation (Case 2). If the air change rate (ACR) is reduced by 50% from normal Case 1, the resulting energy consumption increases. This is because the calculated office space is in cooling conditions for much of the year.

Figure 5 compares IAQ for each case using $OCIOC_{norm}$ for CO_2, focusing only on general IAQ. Case 2 gives the smallest $OCIOC_{norm}$ value. As the maximum opening area increases in Case 3, $OCIOC_{norm}$ values decrease. The 50% reduction of ACR leads to poor IAQ.

Figure 6 shows OAD_{ave} values for air temperature (dimensions in °C). Occupants are exposed to an average temperature deviation of 1.4°C to the + direction and 0.4°C to the - direction from the comfort range. In Case 1, OAD_{ave} values become almost zero. On the other hand, OAD_{ave+} values become larger as the maximum opening area increases in Case 3. However, OAD_{ave+} values remain to be relatively small (around 0.1°C even in case of 13%).

Figure 7 shows the relation among energy consumption, IAQ, and the thermal environment. For the cases studied in this paper, energy consumption and IAQ have win-win relationship while there are tradeoffs between energy consumption and the thermal environment. If we take a closer look at the figure, the characteristics of each system become clearer. For example, natural ventilation without controls (Case 2) is quite effective to conserve energy and to improve IAQ but leads to the poor thermal environment. Mechanical ventilation (Case 1) results in relatively large energy consumption but ensures the good thermal environment. The combination of natural and mechanical ventilation with controls (Case 3) reduces energy consumption and improves IAQ without compromising the thermal environment.

In Figure 8, the relation between energy consumption and IAQ is illustrated in a different way. Energy consumption for HVAC systems is shown on an $LCCO_2$ (Life-Cycle CO_2 measured in mass of C in CO_2 [5]) basis, which represents the impact of HVAC operation on the global environment. The amount of CO_2 inhaled by occupants is expressed on the vertical axis by using the same unit as $LCCO_2$. This value is like "$LCCO_2$ inhaled by occupants" or "$LCCO_2$ - IAQ" and may represent the impact of HVAC systems on IAQ.

Figure 9 illustrates the 3-D relation among energy consumption, IAQ, and the thermal environment. The proposed tool is good at evaluating tradeoffs among these factors and helps to create buildings that are friendly to both the global environment and occupants.

DISCUSSION

1. The integrated dynamic simulation model can quantitatively evaluate the long-term performance of buildings in terms of IAQ, the thermal environment, and energy consumption for HVAC systems. The model is especially good at evaluating the effects of natural and hybrid ventilation, taking transitional behavior of each system into account.
2. Occupant Contaminant Inhalation has a potential to be practically used to evaluate long-term building performance in terms of IAQ. It will be more useful when more knowledge becomes available on dose-response relationship.
3. Occupancy-weighted Accumulated Deviation from thresholds means total exposure levels of occupants to various environmental factors. Application of OAD to other factors than air temperature (e.g., humidity, the thermal radiative environment, or PMV) will be also useful.
4. The proposed design tool will help to create buildings with low energy consumption without compromising comfort and occupant health. However, it treats only operational phases and is a part of the sustainability evaluation of buildings. It should be combined with the environmental assessment for construction, renovation, or demolition phases, and other indoor environmental factors such as the light environment (for example, [2]).

CONCLUSION

Natural ventilation can be quite effective to reduce energy consumption without compromising the thermal comfort and IAQ if ventilation strategies are appropriate. The proposed long-term evaluation model is useful to evaluate various HVAC systems from the viewpoint of both the environmental impact and the indoor thermal and air environment.

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APPENDIX CALCULATION OF VARIOUS OCI VALUES

The following are the procedures for calculating various OCI values *for gaseous contaminants* (e.g., OCI, OCI_{norm}, and OCI_{ave}). The procedures *for particulate matter* are almost the same and can be derived using mass concentration rates and k = 1. For details, see [6].

Occupant Airborne Contaminant Inhalation in Absolute Values (OCI)

$$M_{ci} = k \cdot f_{res} \cdot V_{br} \cdot C \quad \text{(A-1)} \qquad OCI = \int M_{ci} \cdot w_{oc} \cdot dt \quad \text{(A-2)}$$

$$OCI_{norm} = OCI / N_{ro} \quad \text{(A-3)} \qquad OCI_{ave} = OCI / \int w_{oc} \cdot dt \quad \text{(A-4)}$$

$$k = (M \cdot P) / (R \cdot T) \quad \text{(A-5)}$$

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]
- C : Concentration inside the room (volumetric) [-]
- OCI : Total amount of contaminant inhaled by occupants during the period concerned [g] (Occupant airborne Contaminant Inhalation in absolute values)
- w_{oc} : Weighting factor for occupancy [person] t : Time [h]
- OCI_{norm} : Normalized OCI value during the period concerned [g/person]
- N_{ro} : Number of nominal occupancy [person]
- 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)]
- 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]

Occupant Airborne Contaminant Inhalation relative to Outside Concentration (OCIOC)

In order to calculate this value, the equation (A-1) should be replaced by the following equation:

$$M_{ci} = k \cdot f_{res} \cdot V_{br} \cdot (C - C_0) \quad \text{(A-6)}$$

where

C_0 : Outside concentration (volumetric) [-]

OCIOC, $OCIOC_{norm}$, $OCIOC_{ave}$ can be calculated by the same procedures as in the equations (A-2) to (A-4).

Occupant Airborne Contaminant Inhalation above Thresholds (OCIT)

In order to calculate this value, the equation (A-1) should be replaced by the following equations:

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

$$M_{ci} = 0 \quad \text{when } C \le C_{th} \quad \text{(A-7)}$$

where

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

OCIT, $OCIT_{norm}$, $OCIT_{ave}$ can be calculated by the same procedures as in the equations (A-2) to (A-4).