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A New Experimental Approach for the Evaluation of Domestic Ventilation Systems, Part 3—Evaluation of Ventilation Systems for an Entire House

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ABSTRACT

This paper proposes an index for expressing the ventilation characteristics of an entire house to assist in ventilation design. The overall ventilation rate fulfillment (OVRF) index determines supply/exhaust rates with respect to design goals and to their balance in a multi-room house. The authors used the index to evaluate various ventilation systems using experimental results presented in a companion paper, which demonstrated satisfactory application.

The index can represent the degree of fulfillment of the projected ventilation of an entire house. It enables easy determination of the effective operating range of ventilation systems under various conditions, including the airtightness of the house and external conditions. Future study will include qualitative evaluation and development of more accurate measuring methods on site.

INTRODUCTION

Ventilation is essential for maintaining a comfortable indoor environment, and an appropriate ventilation design is necessary since houses today are highly insulated and tightly constructed in order to achieve more energy efficiency.

Because of the increased airtightness of houses, cracks in the envelope are decreased and natural ventilation is reduced. Consequently, the required amount of fresh air is not provided and polluted air is not sufficiently exhausted. On the other hand, excessive ventilation increases the air-conditioning load and may worsen the indoor environment, for example, increasing drafts during heating in winter. Clearly, excessive ventilation is not desirable from the viewpoint either of energy saving or comfort. To provide appropriate ventilation, the entire building must be considered in the ventilation design, and it is important to evaluate to what degree the system fulfills the projected ventilation effect in many conditions.

This paper proposes an index for judging how various residential ventilation systems meet their design targets. Evaluation of the index is based on experimental results for a two-story house with a nonduct exhaust-only ventilation system at different levels of airtightness and inside-outside temperature differences.

PREVIOUS STUDIES

Ventilation Evaluation Indexes Currently Used

Ventilation-related indexes include air change rate, age of air, and ventilation efficiency. The amount of ventilation is expressed by ventilation rate, air change rate, and nominal time constant (reciprocal number of the air change rate). The ventilation rate is the specific volume of ventilation per unit time. Required ventilation rates per occupant for different rooms are recommended for acceptable air quality in rooms. The air change rate indicates the number of changes of indoor air per unit time, taking the volume of the room space into account. According to Japanese practice, if an exhaust-only mechanical ventilation system is installed, an air change rate of approximately 0.5 (1/h) for the overall house is recommended.

The main indexes for the characteristics of the ventilation in a single space are the age of air and air-age-dependent ventilation efficiency (air change efficiency). The age of air is the time required for a fluid to move from an outlet (supply port) in a space to a specified point.

The room "mean age of air," which represents the average for an entire space rather than a specified point, is also used. As the age of air decreases, the time span for fresh air to reach the point decreases. Therefore, it expresses the degree of air freshness.

The room "air change efficiency" is an index that indicates how fast the room air changes. The room air change efficiency is 1.0 for piston flow and 0.5 for complete diffusion.

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TABLE 1
Ventilation Evaluation Indexes

Indexes	Equations	Characteristics
Q (ventilation rate)	(m^3/h)	Amount of ventilation
n (air change rate)	$n = Q/V$ (1/h) Q: ventilation rate (m^3/h) V: room volume (m^3)	Number of changes of air per unit time
$\langle\tau\rangle$ (room mean age of air)	$\langle\tau\rangle = \frac{Q}{V}\int_0^\infty t \cdot \frac{Ce(t)}{C(0)}dt$ (h) $Ce(t)$: Tracer gas concentration of exhaust at time t $C(0)$: First concentration	Average in the entire space of the time for a fluid to move from an outlet in a space to a specified point
ε_a (air change efficiency)	$\varepsilon_a = \tau_n/(2 \cdot \langle\tau\rangle)$ τ_n : nominal time constant (h)(=1/n) $\langle\tau\rangle$: room mean age of air (h)	The index that indicates how fast the room air changes $\varepsilon_a = 1.0$ when piston flow $\varepsilon_a = 0.5$ when complete diffusion

The age of air and ventilation efficiency are usually measured with tracer gas. Studies of measurement methods and many examples of actual measurements in large spaces, such as office buildings and factories, have been reported. Table 1 summarizes the characteristics of the indexes.

Problems of Ventilation Evaluation Indexes

The indexes described above are used to evaluate ventilation volume and quality in a space and to indicate ventilation rate, air freshness, and room air change rate. However, all these indexes refer to a single space. If they are applied to an entire house with multiple rooms, each room is evaluated independently so the overall performance of a ventilation system, including balance between rooms, cannot be evaluated. Thus, it is difficult to apply them to evaluate fulfillment of the ventilation design of an overall residential building.

PROPOSAL OF A NEW INDEX

As a solution for the difficulties noted above, this paper proposes a new ventilation performance evaluation index with the following characteristics.

1. *The characteristics of ventilation of the whole house are expressed by a single value.* This means ventilation systems can easily be compared and evaluated under different conditions and results can be used in the design of a suitable ventilation system.
2. *The balance of the ventilation rate in the whole house is expressed.* The ventilation rate of each room can be evaluated and the balance between rooms can be expressed, so the ventilation design of the entire house can be evaluated.
3. *Evaluation of quantity.* The purpose of installing a residential ventilation system is to provide required air supply to and exhaust from each room of a house and provide ventilation efficiently in each room. Therefore, the evaluation of ventilation includes assessment of the supply and exhaust rates of each room, ventilation quality in each room, and the overall balance. When comparing a quantitative evaluation with a qualitative evaluation, priority is given to the quantity—the age of air and ventilation efficiency should be evaluated after satisfying the requirement for quantity. An ideal index should express all these items, but this paper evaluates quantity alone as the first step.
4. *Air supply is distinguished from exhaust.* A required ventilation rate is recommended for each room to maintain a good indoor environment. However, since ventilation involves air supply and exhaust, the required ventilation may vary with the type of room. For example, the rate for clean zones, such as bedrooms and living rooms, should be considered as the supply rate of fresh air, whereas the ventilation rate of dirty zones, such as toilets and bathrooms, should be considered as the exhaust rate of polluted air. Therefore, the supply rate is distinguished from the exhaust rate, each of them is evaluated separately, and, finally, a value is obtained for the overall ventilation. The index calculation method is described below.

Overall Supply Rate Fulfillment, OSRF

Basic Concept for supply rate fulfillment. First, SRF, i.e., the air supply fulfillment of each room, is defined. Since the index is intended to evaluate quantity, SRF is defined as the ratio of the actual supply rate to the required rate. The ratio expresses the fulfillment for the room.

Specifying the Required Supply Rate for Each Room. The required fresh air supply rate (P_i) is set for each room. P_i is used as the target for the ventilation design, and the house and ventilation system are designed to achieve this value.

The rooms that require fresh air include clean zones, such as bedrooms and living rooms. The main purpose of supplying fresh air to clean zones is to dilute pollutants such as carbon dioxide, which are generated indoors, to the permissible level and exhaust them to the outside. Therefore, it is suitable, for example, to calculate the required quantity of fresh air from the amount of carbon dioxide produced by an adult when he or she rests and the prescribed limit for carbon dioxide. The calculated quantity is specified as the required fresh air supply rate (P_i) for the clean zone. The required ventilation rate is recommended based on this in most cases. Contaminants other than carbon dioxide that are produced indoors include water vapor, body odor, and substances from building materials. When there are several pollutants, the carbon dioxide concentration is generally used as an index for indoor air pollution. The required fresh air supply rate (P_i) is specified for clean zones because air supply is essential there. It is not specified for locations that are occupied less frequently, such as dirty zones and staircases.

Concept of the Effective Fresh Air Supply Rate in Each Room. The actual supply air vs. the required fresh air supply rate (P_i) for a room *i* in the house is considered. For the ventilation in room *i*, the portion of supply air that can contribute to dilution of pollutants is converted to a quantity of fresh air. The converted value is defined as the effective fresh air supply rate (S_i). The SRF of each room is expressed by the ratio of the effective fresh air supply rate (S_i) to the required fresh air supply rate (P_i).

The effective fresh air supply rate (S_i) includes the rate of air that flows directly from vents or cracks in the envelope and air that flows in from another room through cracks in the internal walls or door undercuts. One hundred percent of the air that flows in directly from the outside contributes to dilution of pollutants in room *i*, but air from other rooms might not contribute because of contaminants in the other rooms. Therefore, the following are studied to calculate the effective fresh air supply rate (S_i), which is the substantial fresh air supply rate to the room.

The required fresh air supply rate (P_i) for room *i* is the quantity of fresh air required to dilute the contaminants produced in room *i* to the permissible limit. If the effective fresh air supply rate (S_i) equals the required fresh air supply rate (P_i) for room *i*, the contaminants produced in room *i* are diluted to the permissible limit by the effective fresh air supply rate (S_i). If $S_i > P_i$, the pollutants are diluted below the permissible limit by the effective fresh air supply rate (S_i). In this case, S_i is considered sufficient to dilute the pollutants to the prescribed limit, being capable of diluting the pollutants in other rooms too. For example, if the permissible concentration is σ_c and Q (m^3/h) of a concentration of σ flows out from room *i*, the concentration of $Q \cdot \sigma/\sigma_c$ (m^3/h) is σ_c and the remaining $Q \cdot (1 - \sigma/\sigma_c)$ (m^3/h) can be regarded as fresh air.

Letting $(1-\sigma/\sigma_c) = \alpha$, α is defined as surplus fresh air. α is the concentration based upon that of outside air.

Therefore, the effective fresh air supply rate (S_i) for room *i* includes the quantity of fresh air that flows directly into the room, the quantity of fresh air that moves between rooms, and the quantity of fresh air that flows directly to the outside. It is expressed by the following equation:

$$S_i = A_i + \sum_{j=1}^{N} \max(0, \alpha_j \cdot Q_{j,i}) - \sum_{j=1}^{N} \max(0, \alpha_i \cdot Q_{i,j}) - \max(0, \alpha_i \cdot B_i) \qquad (1)$$

where

S_i = effective fresh air supply rate, the rate of air that contributes to dilution of pollutants in room *i*;

A_i = direct fresh air supply rate, the rate of air that is supplied directly to room *i*;

N = number of rooms (excludes external space, but a mixing box in the duct system may be included);

α_i = surplus fresh air supply rate contained in the air exhausted from room *i*;

$Q_{i,j}$ = rate of air flowing from room *i* to room *j* ($Q_{i,i} = 0$);

B_i = rate of air exhausted directly to the outside from room *i*.

If the air density in the space is assumed constant and the rate of fresh air that flows into or out of room *i* is considered, the following equation is obtained. Equation 2 expresses the law of conservation with regard to the quantity of fresh air that flows into and out of and is used in room *i*.

$$A_i + \sum_{j=1}^{N} \alpha_j \cdot Q_{j,i} - \sum_{j=1}^{N} \alpha_i \cdot Q_{i,j} - \alpha_i \cdot B_i - P_i = 0 \qquad (2)$$

where

P_i = required fresh air supply rate, the supply rate of fresh air required to dilute to the permissible limit pollutants that are predicted to be produced in room *i*.

If the outflow and inflow rates ($Q_{i,j}$) of air between rooms and the outflow and inflow rates (A_i, B_i) of air to the outside are known, unknown values for each room are α_i and S_i, which can be calculated by solving Equations 1 and 2.

Supply Rate Fulfillment for Each Room, SRF. For each room for which a required fresh air supply rate (P_i) is specified, the supply rate fulfillment (SRF) is defined by Equation 3 as the ratio of the effective fresh air supply rate (S_i) to the required fresh air supply rate (P_i) for room *i*.

$$SRF_i = \min\left(\frac{S_i}{P_i - \sum_{j=1}^{N} \min(0, \alpha_j \cdot Q_{j,i})}, 1\right) = \min\left(\frac{S_i}{P_i'}, 1\right) \qquad (3)$$

where

SRF_i = supply rate fulfillment of room *i*,

i = *i*th room for which the required fresh air supply rate (P_i) is specified,

S_i = effective fresh air supply rate (S_i) for room *i*,

P_i = required fresh air supply rate for room *i*,

P_i' = substantial fresh air supply rate for room *i*.

The substantial fresh air supply rate (P_i') is the required rate of fresh air with regard to pollutants that flow in from other rooms. P_i' is calculated by subtracting the negative surplus fresh air supply rate from another room from the required fresh air supply rate (P_i) for room i. This value indicates the rate of fresh air required to dilute to the permissible concentration limit the total quantity of pollutants produced in room i and circulated in from other rooms.

The upper limit of SRF_i is taken as a unity. It is clear that ventilation exceeding the required rate has a good effect on maintenance of indoor air quality, but it is not desirable because the air-conditioning load for the room is increased and the indoor thermal environment can deteriorate. Excessive ventilation should be evaluated unfavorably. However, it is difficult at present to include such influences numerically. The purpose of the index proposed here is limited to quantitative evaluation, so the upper limit is defined by considering whether or not the required rate is provided.

The denominator of Equation 3 becomes zero when the required fresh air supply rate for that room is zero. In such a case, the SRF is not calculated for the room. If the required fresh air supply rate is not specified for the room and pollutants are not circulated into the room from another room, the denominator becomes zero.

If summation of Equation 1 is done for all rooms, the following equation is obtained:

$$\begin{aligned}\sum_{i=1}^{N} S_i = {} & \sum_{i=1}^{N} A + \sum_{i=1}^{N}\sum_{j=1}^{N} \max(0, \alpha_j \cdot Q_{j,i}) - \\ & \sum_{i=1}^{N}\sum_{j=1}^{N} \max(0, \alpha_i \cdot Q_{i,j}) - \sum_{i=1}^{N} \max(0, \alpha_i \cdot B_i) \\ = {} & \sum_{i=1}^{N} A - \sum_{i=1}^{N} \max(0, \alpha_i \cdot B_i) \\ = {} & \sum_{i=1}^{N} A_i - \sum_{i=1}^{N} W_i\end{aligned} \tag{4}$$

$$W_i = \max(0, \alpha_i \cdot B_i) \tag{5}$$

where

W_i = positive surplus fresh air supply volume exhausted from room i to the outside, the rate of fresh air that is exhausted without contributing to dilution of pollutants.

The second term of the right-hand side of the first row of Equation 4 is the total of the positive surplus fresh air supply rate that flows into a room from all the other rooms. The third term is the total of the positive surplus fresh air supply rate that flows out from a room to all the other rooms. Therefore, the second term equals the third term to give Equation 4.

Equation 4 indicates that the sum of the rate of fresh air used to dilute pollutants in each room and the rate of fresh air exhausted to the outside without contributing to dilution of pollutants equal the fresh air supply rate in each room. In other words, fresh air supplied to each room does or does not contribute to dilution of pollutants before it is exhausted.

Overall Supply Rate Fulfillment, OSRF. The overall supply rate fulfillment (OSRF) is defined as follows by using the SRF calculated for each room for which the required fresh air supply rate (P_i) is specified:

$$OSRF = (SRF_1 \times SRF_2 \times \Lambda \times SRF_m)^{1/m} \tag{6}$$

where

OSRF = overall supply rate fulfillment,

m = number of rooms for which the required fresh air supply rate (P_i) is specified.

The overall supply rate fulfillment (OSRF) is a comprehensive evaluation index of ventilation fulfillment for every room. Comprehensive evaluation methods may use either the geometric or the arithmetic mean, which is the simple mean of fulfillments of all rooms. If no air is supplied to one of the rooms for which the required fresh air supply rate (P_i) is specified, the ventilation target of the overall house should be judged as not achieved even if the air supply to all the other rooms is satisfactory. When the arithmetic mean is used and SRF = 0 for one room, it is not reflected in the overall OSRF value if the SRF values for other rooms are high and there are many rooms. Therefore, this paper uses the geometric mean to calculate OSRF to reflect a low OSRF value for one room upon comprehensive evaluation, as defined in Equation 6. If the balance of the fresh air supply is good but the ventilation rate is slightly insufficient for the whole house, it can be increased easily by enhancing the fan power if mechanical ventilation is provided. On the other hand, if the balance is bad, more thorough measures, such as improved airtightness, are necessary. Therefore, the balance should be emphasized for evaluation.

Overall Exhaust Rate Fulfillment, OERF

Basic Concept of Exhaust Rate Fulfillment (ERF) for Each Room. The exhaust rate fulfillment (ERF) for each room is defined as the ratio of the actual exhaust rate to the required exhaust rate in the same way as for the air supply. It is also necessary to consider the air inflow and outflow rates between rooms for exhaust. If polluted air flows to another room from a room for which the required exhaust is specified, the required exhaust rate and the actual rate should be treated as follows.

Required and Actual Exhaust Rates for Each Room. The rooms that require exhaust include dirty zones, such as bathrooms, toilets, and kitchens. In the dirty zones, large quantities of pollutants, water vapor, and odors are produced temporarily. To prevent them from flowing to other rooms, dirty zones should, in principle, be arranged at the downstream end of the airflow path in the building.

As mentioned above, large quantities of pollutants are likely to be produced temporarily in the dirty zones. Thus, the dirty zones are considered as rooms for which a high resistance to pollutants is offered and a higher permissible concentration of pollutants is specified. The clean zones are regarded as rooms for which a low resistance to pollutants is designed and a lower permissible concentration of pollutants is specified. If air flows from a dirty zone to a clean zone and pollutants leak into the clean zone, the outflow of polluted air to other rooms can be evaluated by comparing the concentration of pollutants in the clean zone with the permissible value specified for it. The ratio of the permissible concentration in the clean zone to that in the dirty zone is defined as κ ($\kappa < 1$), which is called the permissible concentration ratio.

Exhaust Rate Fulfillment (ERF) for Each Room. If the purpose of ventilation in the dirty zone is dilution and exhaust, the exhaust rate fulfillment can be assessed by comparing it with the specified fresh air supply rate to the dirty zone in the same way as for supply rate fulfillment. Assuming the actual required fresh air supply rate (P_i') is the required exhaust rate and the effective fresh air supply rate (S_i) is the actual exhaust rate, the ratio between these values is defined as the exhaust rate fulfillment for each room. ERF_i is given by Equation 7 by calculating $_i$ for each room by solving Equation 2, the conservation law of the fresh air supply rate for each room and, from the calculated value, obtaining S_i for the dirty zone from Equation 1.

$$\mathrm{ERF}_i = \min\left(\frac{S_i}{P_i - \sum_{j=1}^{N} min(0, \alpha_j \cdot Q_{j,i})}, 1\right) = \min\left(\frac{S_i}{P_i}, 1\right) \tag{7}$$

However, the surplus fresh air supply rate α_i for each room is the value when the permissible concentration of the dirty zone is used. Thus, the calculated value of α_i cannot be applied as it is to the ERF calculation for clean zones. The calculation method of $\langle\alpha\rangle$ for clean zones is discussed below.

Letting the permissible concentration of the dirty zone be σ_d, the surplus fresh air supply ratio of the dirty zone be α_d, the permissible concentration ratio of the clean zone be $\kappa\alpha_d$, and the surplus fresh air supply ratio of the clean zone be $\langle\alpha\rangle$, the actual concentration σ_r of the pollutants contained in air flowing between rooms is calculated by Equations 8 and 9.

$$\sigma_r = \sigma_d \cdot (1 - \alpha_d) \tag{8}$$

$$\sigma_r = \kappa\sigma_d \cdot (1 - \langle\alpha\rangle) \tag{9}$$

where

σ_r = actual concentration of the pollutants contained in air flowing between rooms,

σ_d = permissible concentration of the dirty zone,

α_d = surplus fresh air supply ratio when the permissible concentration of the dirty zone is applied,

κ = permissible concentration ratio,

$\langle\alpha\rangle$ = surplus fresh air supply ratio when the permissible concentration of the clean zone is applied.

The surplus fresh air supply ratio $\langle\alpha\rangle$ of the clean zone can be expressed by Equation 10, using Equations 8 and 9.

$$\begin{aligned} \langle\alpha\rangle &= 1 - \sigma_r/\kappa\sigma_d \\ &= 1 - (\sigma_d - \sigma_d \cdot \alpha_d)/\kappa\sigma_d \\ &= (\kappa\sigma_d - \sigma_d + \sigma_d\alpha_d)/\kappa\sigma_d \\ &= (\kappa + \alpha_d - 1)/\kappa \end{aligned} \tag{10}$$

For clean zones, $\langle\alpha_i\rangle$ for each room is obtained by Equation 10 from α_i, used in ERF calculations for the dirty zone, and the effective fresh air supply rate $\langle S_i\rangle$, based on the permissible concentration for the clean zone, is calculated from Equation 11.

$$\begin{aligned} \langle S_i\rangle = A_i + \sum_{j=1}^{N} max(0, \langle\alpha_j\rangle \cdot Q_{j,i}) - \\ \sum_{j=1}^{N} max(0, \langle\alpha_i\rangle \cdot Q_{i,j}) - max(0, \langle\alpha_i\rangle \cdot B_i) \end{aligned} \tag{11}$$

where

$\langle S_i\rangle$ = effective fresh air supply rate for room i, based on the permissible concentration for the clean zone;

$\langle\alpha_i\rangle$ = surplus fresh air supply ratio for room i, based on the permissible concentration for the clean zone.

The ERF for the clean zone is defined by Equation 12 using the effective fresh air supply rate $\langle S_i\rangle$ for each room obtained by Equation 11.

$$\mathrm{ERF}_i = \min\left(\frac{\langle S_i\rangle}{P_i - \sum_{j=1}^{N} \min(0, \langle\alpha_j\rangle \cdot Q_{j,i})}, 1\right) = \min\left(\frac{\langle S_i\rangle}{P_i}, 1\right) \tag{12}$$

The required exhaust rate (P_i) is set to zero for the clean zone. If polluted air flows in from the dirty zone and the substantial required fresh air supply (P_i') occurs, the ERF is calculated using Equation 12 for rooms other than the dirty zone. The actual house has spaces such as staircases that are not dirty or clean zones. They are treated as clean zones here. Therefore, the ERF is calculated using Equation 12 for all rooms that are not in dirty zones.

Overall Exhaust Rate Fulfillment. The above ERF calculation method considers one type of pollutant. The actual house has several dirty zones, and an exhaust fan is installed in each dirty zone. The pollutants produced in dirty zones are not the same. For example, pollutants include water vapor produced in a bathroom, odor in a toilet, and oil mist and exhaust in a kitchen. The ERF for each room can be calculated for each pollutant by setting several κ values according to the

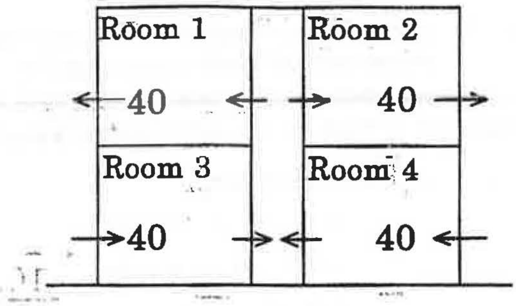

Figure 1-1a Natural ventilation I.

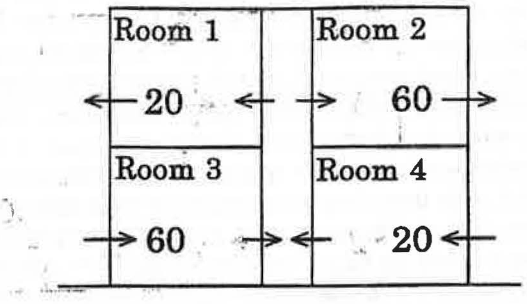

Figure 1-1b Natural ventilation II.

type of pollutant. Therefore, the overall exhaust rate fulfillment $OERF_p$ for a pollutant P is defined by Equation 13.

$$OERF_p = (ERF_{p1} \times ERF_{p2} \times \Lambda \times ERF_{pn})^{1/pn} \quad (13)$$

where

$OERF_p$ = overall exhaust rate fulfillment for pollutant P,
ERF_p = exhaust rate fulfillment for pollutant P,
pn = number of rooms for which ERF_p is calculated.

The overall exhaust rate fulfillment OERF is defined by Equation 14 as the geometric mean of $OERF_p$ for each pollutant.

$$OERF = (OERF_1 \times OERF_2 \times OERF_d)^{1/d} \quad (14)$$

where

OERF = overall exhaust rate fulfillment,
d = type of pollutant.

Overall Ventilation Rate Fulfillment, OVRF

The overall ventilation rate fulfillment (OVRF) is obtained by Equation 15 from the calculated OSRF and OERF. Since ventilation in a house always involves air supply and exhaust, the geometric mean of OSRF and OERF is not used to calculate OVRF.

$$OVRF = OSRF \times OERF \quad (15)$$

where

OVRF = overall ventilation rate fulfillment.

EXAMPLE OF APPLICATION OF OVRF TO VENTILATION SYSTEMS

Actual ventilation includes natural ventilation due to differences of temperature inside and outside the house (buoyancy), ventilation due to wind, and mechanical ventilation. Mechanical ventilation includes natural air supply plus mechanical exhaust as well as mechanical air supply plus mechanical exhaust. This section describes with simple examples how the index proposed in this paper is applicable to various ventilation systems.

Natural Ventilation

Examples of air flow when ventilation occurs due to temperature difference in a two-story house are shown in Figures 1-1a (natural ventilation I) and 1-1b (natural ventilation II). It is assumed that with heating in winter, the indoor temperature is higher than that outdoors. For example, the required fresh air supply rate (P) for each room is 20, but the value of (P) is not specified for the staircase at the center of the house. No dirty zones are defined, and only OSRF is calculated. The calculation results are given in Table 2a.

TABLE 2a
Calculation Result of Natural Ventilation

	Natural Ventilation I					Natural Ventilation II				
	R.1	**R.2**	**R.3**	**R.4**	**S.C.**	**R.1**	**R.2**	**R.3**	**R.4**	**S.C.**
α	0.0	0.0	0.5	0.5	0.5	-0.5	0.17	0.67	0.0	0.5
S	20.0	20.0	20.0	20.0	0.0	10.0	20.0	20.0	20.0	0.0
P	20.0	20.0	20.0	20.0	-	20.0	20.0	20.0	20.0	
P'	20.0	20.0	20.0	20.0	-	20.0	20.0	20.0	20.0	
W	0.0					10.0				
SRF	1.0	1.0	1.0	1.0	-	0.5	1.0	1.0	1.0	-
OSRF	1.0					0.84				

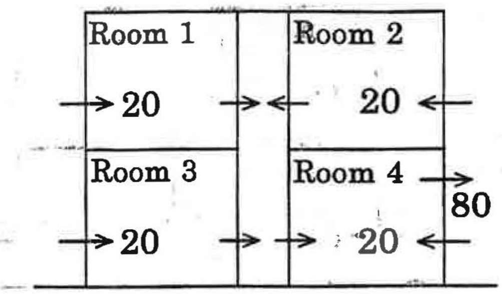

Figure 1-2a Mechanical ventilation I.

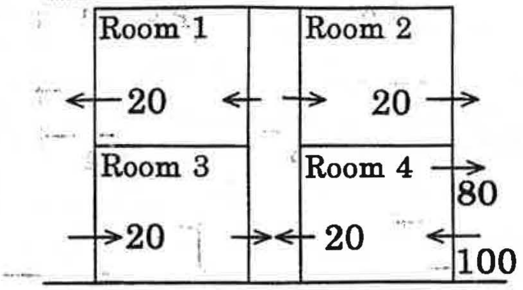

Figure 1-2b Mechanical ventilation II.

With natural ventilation I, fresh air does not flow into rooms 1 and 2, but as α > 0, surplus fresh air is produced in rooms 3 and 4, and, consequently, air is supplied to rooms 1 and 2. Therefore, SRF = 1 for each room.

With natural ventilation II, we consider an example where the balance between air supply and exhaust is lost due to the influence of wind. In room 1, $S_i = 10$, and SRF1 becomes lower, i.e., 0.5, but the SRF value does not decrease for the other rooms. The overall ventilation rate for this house is 80, and the total of the S values of all rooms is 70. This is due to the fact that some fresh air flowed out without contributing to dilution of pollutants. If the fresh air supply rate (W) that does

TABLE 2b
Calculation Result of Mechanical Ventilation

	Mechanical Ventilation I					**Mechanical Ventilation II**				
Calculation of OSRF										
	R.1	**R.2**	**R.3**	**R.4**	**S.C.**	**R.1**	**R.2**	**R.3**	**R.4**	**S.C.**
α	0.0	0.0	0.0	0.0	0.0	−0.5	−0.5	0.0	1.0	0.5
S	20.0	20.0	20.0	0.0	0.0	10.0	10.0	20.0	0.0	0.0
P	20.0	20.0	20.0	-	-	20.0	20.0	20.0	-	-
P'	20.0	20.0	20.0	-	-	20.0	20.0	20.0	-	-
W					0.0					60.0
SRF	1.0	1.0	1.0	-	-	0.5	0.5	1.0	-	-
OSRF					1.0					0.63
Calculation of OERF (κ = 0.1)										
α	1.0	1.0	1.0	0.0	1.0	0.625	0.625	1.0	0.25	0.625
S				60.0	-	-	-	-	60.0	-
P	-	-	-	60.0	-	-	-	-	60.0	-
P'	-	-	-	60.0	-	-	-	-	60.0	-
ERF	-	-	-	1.0	-	-	-	-	1.0	-
⟨α⟩	1.0	1.0	1.0	(−9)	1	−2.75	−2.75	1	(−6.5)	−2.75
⟨*S*⟩	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	-	20.0
⟨*P*⟩	0.0	0.0	0.0	-	0.0	0.0	0.0	0.0	-	0.0
⟨*P'*⟩	0.0	0.0	0.0	-	0.0	55.0	55.0	0.0	-	130.0
ERF	-	-	-	-	-	0	0.0	-	-	0.154
OERF					1.0					0.0
Calculation of OVRF										
					1.0					0.0

TABLE 2c
Calculation Result of Duct Central Air-Conditioning System

	System I				System II					
	R.1,2,3	R.4	S.C.	AHU	R.1	R.2	R.3	R.4	S.C.	AHU
Calculation of OSRF										
α	0.0	0.0	0.0	0.5	0.17	0.0	-0.5	0.0	0.0	0.5
S	20.0	0.0	0.0	0.0	20.0	20.0	10.0	0.0	10.0	0.0
P	20.0	-	-	-	20.0	20.0	20.0	-	-	-
P'	20.0	-		-	20.0	20.0	20.0	-	-	-
W				0.0						0.0
SRF	1.0	-	-	-	1.0	1.0	0.5	-	-	
OSRF				1.0						0.79
Calculation of OERF (κ = 0.01)										
α	1.0	0.0	1.0	1.0	1.0	1.0	1.0	0.0	1.0	1.0
S	0.0	60.0	0.0	0.0	0.0	0.0	0.0	60.0	0.0	0.0
P	-	60.0	-	-	-	-	-	60.0	-	
P'	0.0	60.0	0.0	0.0	0.0	0.0	0.0	60.0	0.0	0.0
ERF	-	-	-	1.0	-	-	-	1.0	-	
$\langle\alpha\rangle$	1.0	(−99)	1.0	1.0	1.0	1.0	1.0	(−99)	1.0	1.0
$\langle S\rangle$	0.0	-	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0
$\langle P\rangle$	0.0	-	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0
$\langle P'\rangle$	0.0	-	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0
ERF					-	-	-	-	-	
OERF				1.0						1.0
Calculation of OVRF										
				1.0						0.79

not contribute to dilution of pollutants is added to the sum of S values, the result agrees with the overall ventilation rate.

If the balance between rooms is lost, as in this example, it is clear that the OVRF value can express deterioration of ventilation performance in the entire house with the overall ventilation rate kept constant.

Mechanical Ventilation

Figure 1-2a (mechanical ventilation I) and Figure 1-2b (mechanical ventilation II) illustrate examples of calculation when an exhaust fan is installed assuming that one room of the house is a dirty zone. The required fresh air supply rate (P) is assumed to be 20, and rooms 1 to 3 are regarded as clean zones. For the required exhaust rate, the required fresh air supply rate (P) is to be assumed 60 only for room 4 in which an exhaust fan is installed, and it is not specified for the other rooms. The permissible concentration ratio (κ) of other rooms to room 4 is set to 0.1. The calculation results are summarized in Table 2b.

With mechanical ventilation I, air is supplied in good balance in rooms 1 to 3. Hence, OSRF = 1. Since air is exhausted from room 4, OERF = 1, and as a result, OVRF = 1.

Mechanical ventilation II shows the behavior that can be observed when ventilation driven by mechanical force and ventilation by buoyancy occur at the same time. SRF = 1 for room 3 only, SRF = 0.5 for rooms 1 and 2, and OSRF is 0.63. The ratio (W) of fresh air that does not contribute to dilution of pollutants is 60, which indicates that 60% of the total air supply for the whole house does not contribute to ventilation and is exhausted.

Let us look at the data of OERF. Though the ERF for room 4 is 1, air flows from room 4 to rooms 1 and 2, causing required exhaust ($P'_1 = P'_2 = 55$). Since the effective fresh air supply rates for both rooms are zero, the ERF for rooms 1 and 2 is zero. Accordingly, OERF = 0 and OVRF = 0. The ERF for spaces other than dirty zones is affected by the permissible concentration ratio (κ). It is estimated that if κ is set near to 1, the ERF value increases, and if κ is set near to 0, the ERF value decreases. Therefore, a suitable κ must be selected for

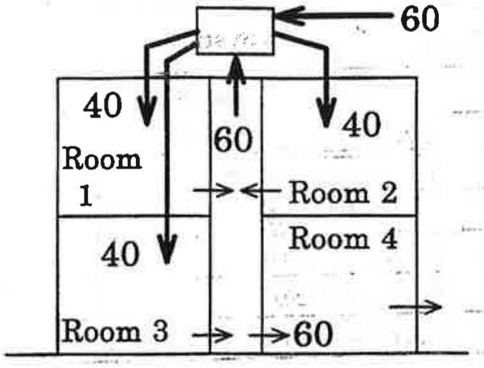

Figure 1-3a Duct central air-conditioning system I.

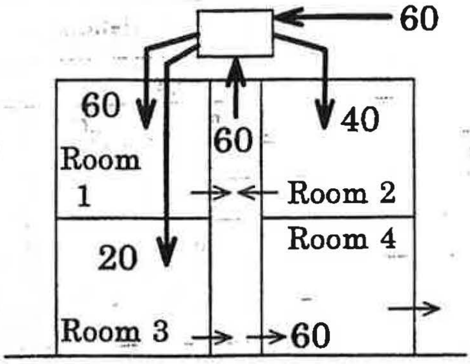

Figure 1-3b Duct central air-conditioning system II.

each pollutant. In fact, the value of κ should be studied further.

Central Air-Conditioning System

An example of a central air-conditioning system used with a ventilating system is given in Figure 1-3a (duct central air-conditioning system I) and Figure 1-3b (duct central air-conditioning system II). As in the example of mechanical ventilation, rooms 1 to 3 are regarded as clean zones and have air conditioning and fresh air supply and room 4 is regarded as a dirty zone and has mechanical ventilation. The required supply rate rooms 1 to 3 is 20, and the specified exhaust rate for room 4 is 60.

In central air-conditioning system I, fresh air is distributed to each room uniformly by an air conditioner. SRF = 1 for each room, so OSRF = 1. The exhaust rate is 60 for room 4, thus, OERF = 1.

In central air-conditioning system II, the overall circulation rate and ventilation rate for the house are the same as for system I, but the balance between rooms is lost. As in the example of mechanical exhaust, the effective fresh air supply rate (S) for rooms 1 and 2 is 20, which satisfies the requirement, but the effective fresh air supply rate (S) decreases for room 3 where the duct air supply rate is small. The OSRF value is less than 1, namely, 0.79, showing a decrease in airflow balance. In this example, the effective fresh air supply rate for the staircase is 10, and the portion corresponding to the decrease in room 3 is supplied to the staircase. The total effective fresh air supply rate is equal to that of system I.

If the index proposed in this paper is applied to systems where circulated air and fresh air are mixed, such as ducted central air conditioning, their performance as a ventilation system can be evaluated. This, too, demonstrates the applicability of OVRF.

EXAMPLE OF OVRF CALCULATION USING EXPERIMENTAL RESULTS

Experimental Conditions

The OVRF value when air was exhausted from one room of a two-story residential house has been calculated using the results of measurements reported in the companion paper and is discussed below.

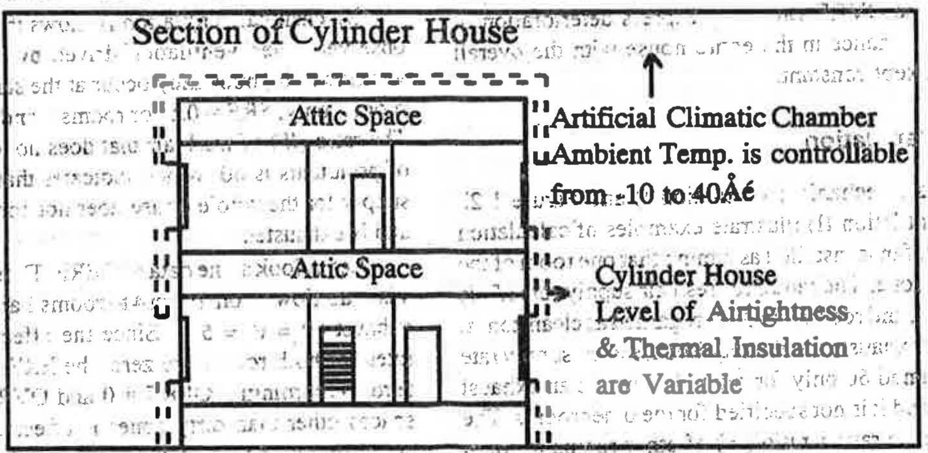

Figure 2 Outline of cylinder house and artificial climatic chamber.

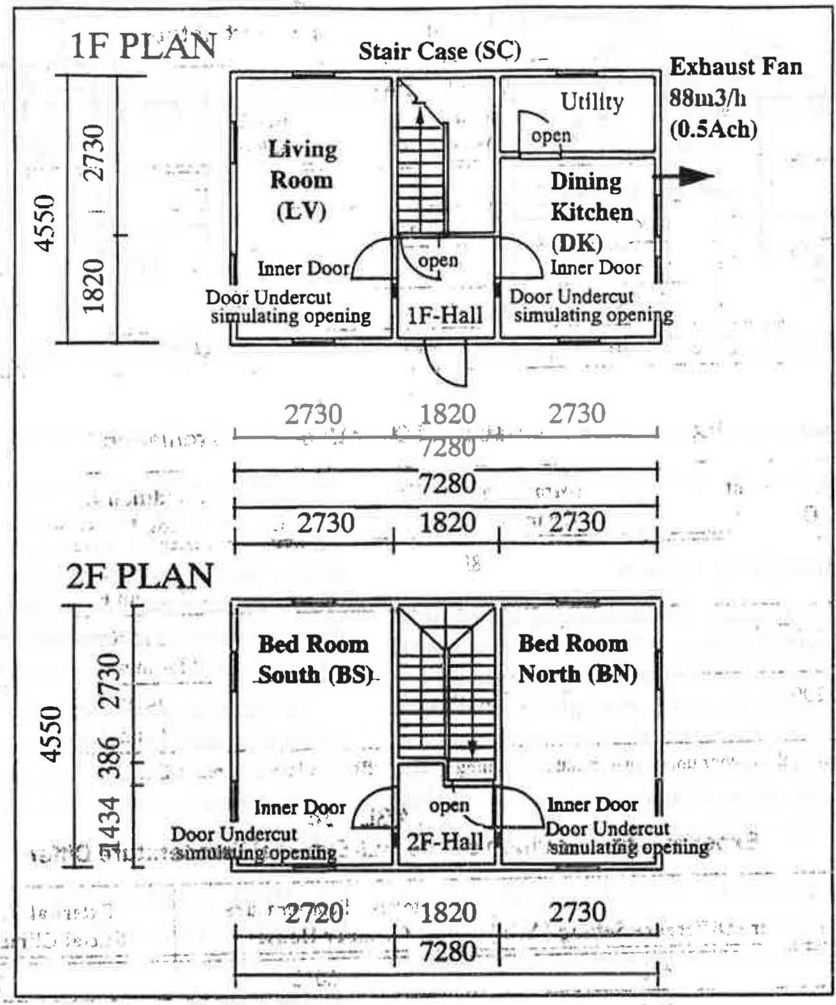

Figure 3 - Plan of cylinder house.

The experimental house was built in an artificial climate chamber that is free of wind and can control temperature and humidity. Its total floor area is about 66 m^2 and the total volume of the rooms is 176 m^3 (see Figures 2 and 3). There are 218 cylinders 50 mm in diameter, with an effective leakage area of 17 cm^2 for airtightness adjustment, in the inner and outer walls of the house. The overall airtightness of the house can be controlled in a range from 0.2 to 40 cm^2/m^2 by opening and closing the cylinders. The most airtight doors are used as inner doors between doors. The effective leakage area of each door undercut can be controlled by changing the lid size of a cylinder that has an inner diameter of 200 mm and is installed near the door to simulate a door undercut.

The house has two rooms, a dining kitchen (DK) and a living room (LV), on the first floor; two rooms, a north bedroom (BN) and a south bedroom (BS), on the second floor; and a staircase (SC). Experiments were performed on these five spaces. Doors between the kitchen and utility area, between the staircase and the first floor hall, and between the staircase and the second floor hall were always open. An exhaust fan was installed in the DK and controlled by an inverter so that the fan exhausts 88 m^3/h. This exhaust corresponds to an overall air change rate of 0.5 ACH/h.

The experimental conditions are summarized in Tables 3a, 3b, and 3c. Experiments were conducted on a total of 60 cases: five levels of airtightness, three areas of door undercut effective leakage, and four temperature differences between the inside and the outside of the house. The volume of the air flowing through each cylinder was calculated from the pressure differences across them and the ΔP-Q characteristics of each cylinder were determined before the tests.

Specifying the Required Fresh Air Supply Rate and Required Exhaust Rate

The four rooms of the house were regarded as clean zones, and the required supply rate, which was a quarter of the exhaust rate (22 m^3/h), was specified for each room.

TABLE 3a
Experimental Condition of Airtightness

Airtightness	Opened Cylinder in Four Rooms	Basic Effective Leakage Area in Whole House	Total Effective Leakage Area	Effective Leakage Area / Floor Area	n50 Value
Level 1	15.5 cm^2 × 1	17 cm^2	79 cm^2	1.2 cm^2/m^2	1.6
Level 2	15.5 cm^2 × 2	17 cm^2	140 cm^2	2.1 cm^2/m^2	2.7
Level 3	15.5 cm^2 × 3	17 cm^2	202 cm^2	3.0 cm^2/m^2	3.9
Level 5	15.5 cm^2 × 5	17 cm^2	325 cm^2	4.9 cm^2/m^2	6.2
Level 10	15.5 cm^2 × 10	17 cm^2	633 cm^2	9.6 cm^2/m^2	11.9

TABLE 3b
Experimental Condition of Door Undercut-Simulating Opening

Diameter of Undercut Simulating Opening	ΔP(Mmaq)-q(M^3 / H) Characteristic	Air Condition at ΔP-q Characteristic Measurement	Effective Leakage Area
U.C. ϕ 50mm	$Q = 24.38P^{1/2}$	24.0°C 755.6 mm Hg	17 cm^2
U.C. ϕ 160mm	$Q = 199.61P^{1/2}$	26.5°C 755.4 mm Hg	136 cm^2
U.C. ϕ 200mm	$Q = 327.46P^{1/2}$	26.0°C 755.8 mm Hg	223 cm^2

Note: in the description below, door undercut-simulating opening as U.C. effective leakage area as E.L.A.

TABLE 3c
Experimental Condition of Internal-External Temperature Difference

Temperature Difference Setting (ΔT)	Internal Temperature (Cylinder House)	External Temperature (Artificial Climatic Chamber)
0°K	20°C	20°C
10°K	30°C	20°C
20°K	30°C	10°C
30°K	40°C	10°C

Only the DK from which air was exhausted was considered as a dirty zone, and the exhaust fan capacity of 88 m^3/h was used as the required exhaust rate for the DK. Therefore, the DK was regarded as a clean zone and dirty zone at the same time. It was assumed that $\kappa = 0.01$. Since this experiment kept the exhaust capacity at 88 m^3/h, the exhaust rate did not change. If negative surplus fresh air does not flow to another room from the DK, the ERF is calculated for the DK only, so OERF = 1.

OVRF Calculation Results

The distribution of the OVRF value with door undercuts 160 mm in diameter is shown in Figure 4. The abscissa represents the airtightness level and the ordinate the temperature difference between the inside and outside of the house. Figure 4 shows that the OVRF is high when the airtightness level is high and the internal-external temperature difference is small. The OVRF is about 1 when the airtightness level is 5 and the temperature difference is 30 K. In the other areas, the OVRF is lower, about 0.6 at the minimum.

Effective Operating Range of the Ventilation System

The ventilation system works properly in the range in which the OVRF value is high, as shown in Figure 4. Therefore, it is clear that the ventilation system works properly when the airtightness level is high and the temperature difference is small. In some cases, as described earlier, the OVRF value is high even if the airtightness level is 5. The distribution of fresh air (W) exhausted to the outside without contributing to dilution of pollutants is shown in Figure 5. The figure shows that as the airtightness level becomes lower and the temperature difference increases, the value of W increases. The cause seems to be that, although the ventilation rate with the exhaust

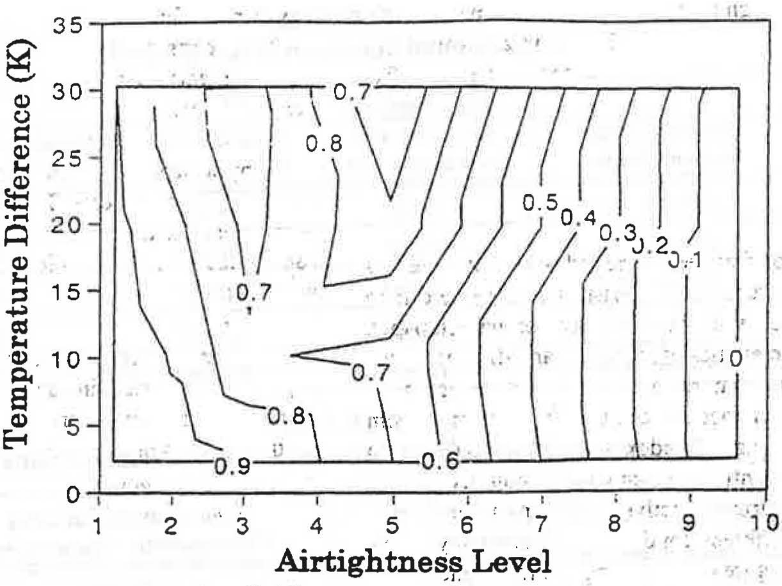

Figure 4 Distribution of OVRF.

fan is kept constant, the natural ventilation induced by buoyancy is accelerated when the temperature difference is increased and the airtightness is lowered; consequently, the overall ventilation rate is increased more than necessary. Since the value of W is actually the fresh air that does not contribute to ventilation, it should be kept low to reduce the air-conditioning load and maintain a comfortable indoor thermal environment. Therefore, low levels of airtightness are not desirable for ventilation design because the value of W is high even if the OVRF value is high. On the other hand, with higher airtightnesses, the value of W is almost zero. In practice, the ventilation system works effectively in one of the two areas with higher OVRF (shown in Figure 4), where the airtightness level is great and the temperature difference is small.

Figure 4 also shows that the OVRF is affected not only by the level of airtightness but the internal-external temperature difference. In an actual house, the level of airtightness and size of door undercut are constant, but the internal-external temperature difference is not constant and varies daily and yearly. The ventilation system operation point is expected to move on a vertical line of the graph. Since the ventilation design should be achieved over a year, the ventilation system operation line should be entirely within the high OVRF area. Hence, if the range of OVRF > 0.8 is considered to be satisfactory, the conditions for effective operation of the ventila-

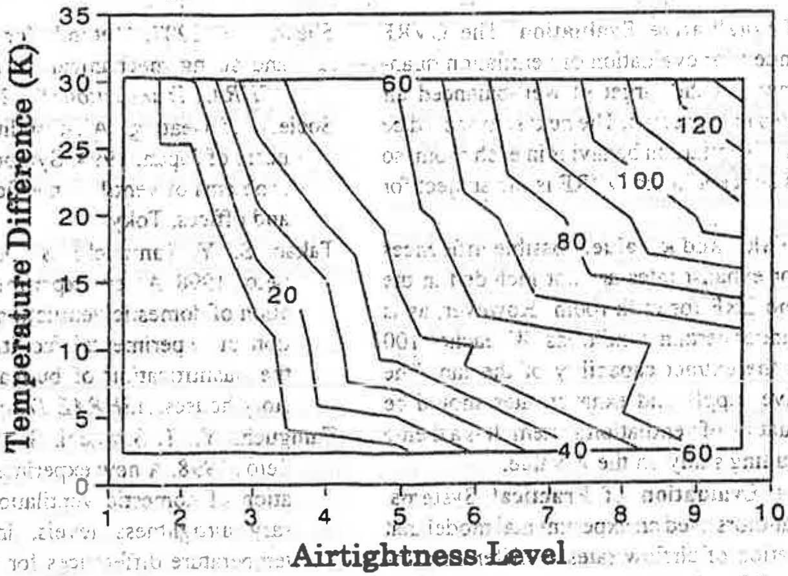

Figure 5 Distribution of W.

tion system are an airtightness level ≥2 for internal-external temperature differences from 0 to 20°C and an airtightness level ≥ 1.5 where the temperature difference varies from 0 to 30°C.

EXAMINATION OF THE INDEX

Validity of OVRF

One of the major features of the index proposed here is that the overall ventilation characteristics of a house can be expressed by a single value. As stated in a companion paper, the ventilation characteristics of the house are affected by the internal-external temperature difference and airtightness. Also, the ventilation characteristics differ from room to room in the house. By using an index such as OVRF, which expresses the overall ventilation behavior of a house, the range of parameters for ensuring effective operation of the ventilation system under different conditions can be easily determined, as shown in Figure 4. Accordingly, such an index will be a powerful aid in the design and evaluation of the house and ventilation.

The OVRF is capable of evaluating the influence of wind, although this was not done in the series of experiments reported here. Previous studies have considered wind to be just an element accelerating the natural ventilation. Actually, the pressure variation due to wind differs between the windward and leeward sides. Therefore, it is incorrect to treat wind always as an element that accelerates ventilation when evaluating ventilation performance for each room. Since the OVRF expresses the ventilation behavior of the whole house on the basis of airflows between rooms, regardless of the type of ventilation driving force, it can evaluate wind influence as an element of ventilation.

Subjects for Further Study

Introduction of Qualitative Evaluation. The OVRF proposed here is an index for evaluation of ventilation quantity, enabling fulfillment of the target of well-balanced air supply and exhaust rates in the rooms. The next step should be qualitative evaluation of ventilation behavior in each room, so the integration of this concept in the OVRF is the subject for future research.

Study of the *W* Value and *k* Value. Possible influences of excessive supply or exhaust rates are not included in the calculation of SRF and ERF for each room. However, as is clear from Figure 5, under certain conditions, *W* reaches 100 m^3/h, which exceeds the extract capability of the fan. The drawbacks of excessive supply and exhaust rates should be considered in the evaluation of ventilation system. It is a theme for further study, including study on the κ value.

Problems in the Evaluation of Practical Systems. Since the tests by the authors used an experimental model that allows easy determination of airflow rates at different locations in the house, OVRF values were easily calculated. In actual ventilation systems installed in real houses, it is generally very difficult to precisely determine the airflow rates in different parts of the house. For example, accurate on-site measurements of the airflow rate across each of the building elements, such as windows and doors, are very difficult. Therefore, it is unavoidable at present to avoid using a technique by which the flow rates are estimated from the properties of building elements. The use of tracer gas is an evaluation technique for actual ventilation systems, but that strategy, too, cannot accurately determine the air flow in an entire house with multiple zones.

Consequently, considering the present state of technology, it can be concluded that a numerical-experimental approach is useful in designing houses and ventilation systems. By studying various alternative ventilation systems for the house to be designed and by calculating OVRF values under different conditions, it is easy to determine the required level of airtightness and specifications of the ventilation system.

CONCLUSIONS

This paper has proposed an index—overall ventilation rate fulfillment (OVRF)—for expressing the ventilation characteristics of an entire house and confirmed its validity using experimental results from a companion paper. The conclusions arrived at in this study were the following.

1. OVRF enables easy determination of the range of different parameters for fulfilling a projected ventilation effect.
2. Introduction of a yearly average allows the evaluation of ventilation systems in which actual conditions are well reflected.
3. Qualitative evaluation and development of new measurement techniques on site are subjects for future study.

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