A New Experimental Approach for the Evaluation of Domestic Ventilation Systems, Part 2—Necessary Airtightness Levels, Inner Door Conditions, and Temperature Difference for Successful Function of Nonduct Exhaust-Only Ventilation System

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ABSTRACT

This paper discusses in detail the behavior of a nonduct exhaust-only ventilation system in an experimental house for which the outflow-inflow paths (i.e., simple openings such as vents and cracks in the envelope, undercuts in inner doors) are modeled by very simple cylinders. The test equipment presented here is composed of a full-scale house model located in an artificial climate chamber where the influence of wind is minimized as much as possible, thereby offering accurately controlled internal-external temperature differences. A series of experiments with this equipment has made it possible to evaluate the effects of various parameters under the same conditions (airtightness of house, size of undercuts in inner doors, internal-external temperature difference), which was impossible in the on-site measurements.

From experimental results, it has been demonstrated that in an extremely airtight house, stable ventilation almost unaffected by an internal-external temperature difference can be achieved by a nonduct exhaust-only ventilation system with a single exhaust fan continually operated, if suitable door undercuts are provided. It has also been verified that at a certain low level of airtightness, the system does not work efficiently, and that in a house where the area of cracks in the envelope is too large, sufficient negative pressure cannot be generated by a single fan. Such a house is, therefore, unsuitable for being ventilated by the exhaust-only technique.

INTRODUCTION

Along with the improvement of airtightness and insulation of houses in recent years, appropriate ventilation planning on which less stress was placed before the advent of a higher airtightness concept has become a vital factor in house design. In a highly insulated and airtight single-family house or a multifamily residential building made of reinforced concrete, the nonsystematic (unintended) reduction of cracks leads to the decrease of fresh air infiltration and may degrade the indoor environment unless correct ventilation design and well-planned operation of the ventilation system are ensured. Thus, introduction of an appropriate ventilation design accompanying mechanical ventilation should be recommended for airtight houses if the required ventilation is not achieved by natural ventilation alone.

This paper deals with an exhaust-only ventilation system that is an example of a mechanical ventilation scheme for residential buildings. This paper treats minutely the air outflow-inflow patterns, aimed at specifying the building performance, and internal-external temperature difference for the satisfactory function of the ventilation system. This type of ventilation keeps the indoor space negatively pressurized by continually operating exhaust fan(s) at an appropriate flow rate, thereby

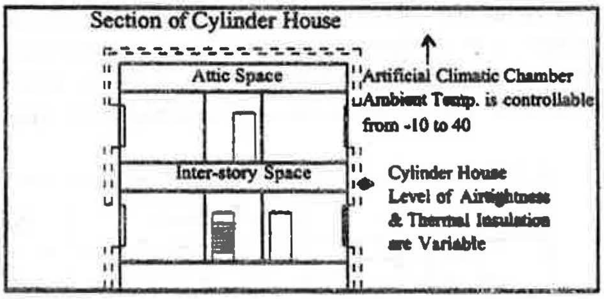

Figure 1 *Outline of cylinder house and artificial climate chamber.*

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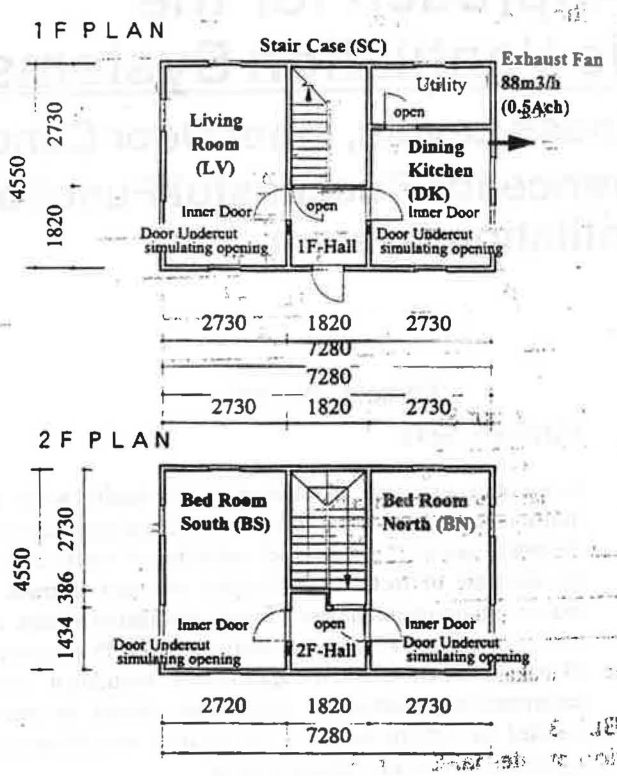

Figure 2 Plan of cylinder house.

accelerating the inflow of fresh air through vents or the like in the envelope. If a single exhaust fan is used, it should be located in the dirty space because a single exhaust fan installed in a clean room will introduce the contaminated air of the dirty space into the clean space. The simplest way of achieving such a ventilation system is, therefore, to continually operate an exhaust fan in the hood over the gas range in the kitchen, in the bathroom, or the lavatory. Since exhaust fans like the one incorporated in the experimental system are found in almost all dwelling units in Japan, it is possible to readily improve the ventilation performance of existing buildings if the requirements for the building and the fan are satisfied. In this sense, the results of the present study will be applicable not solely to the ventilation planning for new buildings but also to the improvement of the environment of existing houses.

From the companion paper that dealt with ventilation due to buoyancy (Sawachi 1997), it was demonstrated that in ordinary airtight houses where no measures for increasing the natural ventilation (e.g., stack effect) are taken (Shaw 1982; ASHRAE 1985), the fresh air supply rate by natural ventilation may not reach the desired level. One solution for achieving the necessary ventilation rate may be the use of a mechanical fan. This paper reports the results of the study on the exhaust-only ventilation system, which is a primary component of mechanical ventilation. The experimental equipment employed is not designed to simulate the wind pressure or non-steady-state conditions. It can, however, determine with satisfactory preciseness the influence of such factors as internal-external temperature difference, undercut size, airtightness, and the airflow pattern. Since this technique is independent of fluctuating factors, the experimental results given in this paper offer a reliable design guideline for a nonduct exhaust-only ventilation system, as well as fundamental data for verifying the accuracy of multizone computer modeling.

EXPERIMENTAL EQUIPMENT AND CONDITIONS

The tests were conducted with a cylinder house constructed in an artificial climate chamber that enabled accurate temperature control, free of influence by wind (see Figure 1). The cylinder house is a two-story residential building with a total floor area equaling 66.25 m^2 and a total volume in the rooms of 176.09 m^3. In every test, the three inner doors were always open: the door between the first-floor utility room and dining kitchen, the door between the first-floor hall and staircase, and the door between the second-floor hall and staircase. Thus, the internal space is composed of a single zone including mainly a staircase and four rooms of the same volume. In the description below, the first-floor dining kitchen and first-floor

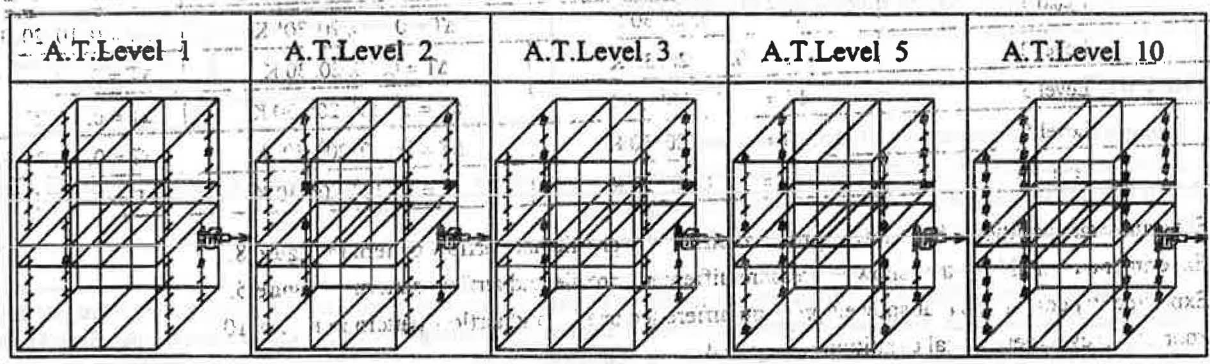

Figure 3 Position of opened cylinders.

TABLE 1
Experimental Conditions 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 2
Experimental Condition of Door Undercut Simulating Opening

Diameter of undercut simulating opening	ΔP (Pa) - Q(m^3/h) characteristic	Air condition at ΔP-Q characteristic measurement	Effective leakage area
U.C. ϕ 50 mm	$Q = 7.79 \times \Delta P^{1/2}$	24.0°C, 1007.4 hPa[1]	17 cm^2
U.C. ϕ 160 mm	$Q = 63.79 \times \Delta P^{1/2}$	26.5°C, 1007.1 hPa	136 cm^2
U.C. ϕ 200 mm	$Q = 104.75 \times \Delta P^{1/2}$	26.0°C, 1007.7 hPa	223 cm^2

[1] Note: Door undercut simulating opening as U.C. ϕ and effective leakage area as ELA

TABLE 3
Experimental Condition of Internal-External Temperature Difference

Temperature difference setting (ΔT)	Internal temperature (cylinder house)	External temperature (artificial climate 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

TABLE 4
Combination of Three Factors in All Experiments

Airtightness	Door undercut simulating opening		
	U.C. ϕ 50 mm	U.C. ϕ 160 mm	U.C. ϕ 200 mm
Level 1	ΔT = 0, 10, 20, 30 K	ΔT = 0[1], 10, 20, 30[1] K	ΔT = 0, 10, 20, 30 K
Level 2	ΔT = 0, 10, 20, 30 K	ΔT = 0, 10, 20, 30 K	ΔT = 0, 10, 20, 30 K
Level 3	ΔT = 0[2], 10, 20[2], 30 K	ΔT = 0[2], 10[3], 20[2], 30 K	ΔT = 0, 10, 20, 30 K
Level 5	ΔT = 0[4], 10, 20, 30 K	ΔT = 0[1], 10, 20[5], 30[1] K	ΔT = 0, 10, 20, 30 K
Level 10	ΔT = 0[4], 10, 20, 30 K	ΔT = 0[4], 10[5], 20[5], 30 K	ΔT = 0[4], 10, 20, 30 K

[1] Experimental conditions that showed pressure difference profile and airflow pattern in Figure 8.
[2] Experimental conditions that showed pressure difference profile and airflow pattern in Figure 5.
[3] Experimental conditions that showed pressure difference profile and airflow pattern in Figure 10.
[4] Poor accuracy experimental condition in Figure 4.
[5] Experimental conditions that showed airflow pattern in Figure 6.

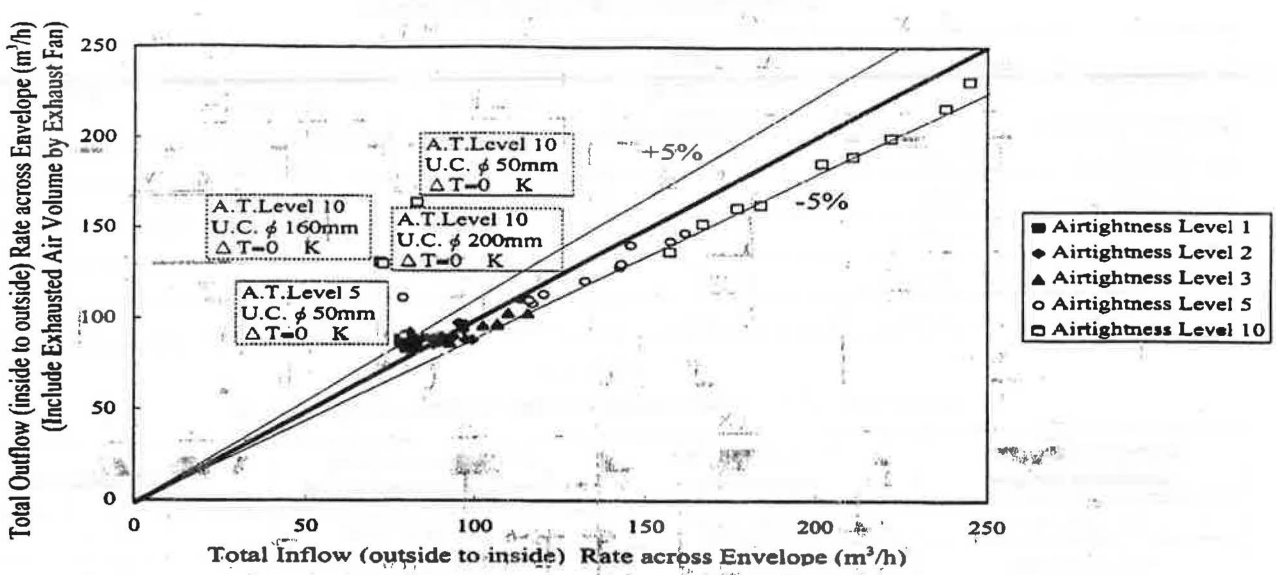

Figure 4 *Outflow-inflow balance.*

utility room, first-floor living room, second-floor bedroom north, and second-floor bedroom south are referred to as DK, LV, BN, and BS, respectively. The entire first-floor hall, second-floor hall, and staircase are referred to as "staircase" (SC) (see Figure 2). The following are the three main characteristics of the cylinder house.

- The airtightness of the envelope is enhanced to the maximum possible extent. The airtightness can be controlled by 218 cylinders, 163 installed in the external walls and 55 in the internal walls.

- For each of the four inner doors between SC and DK, SC and LV, SC and BN, and SC and BS, an airtight door designed for installation in an external wall is used so that the outflow and inflow rates through the doors are minimized. A door undercut simulating an opening is provided in the vicinity of each door. Adjustment of its opening area enables the simulation of various sizes of door undercut.

- Since the P-Q characteristics of all the cylinders (airtightness control cylinders in internal and external walls) and undercut-simulating openings are known, it is possible to obtain the airflow rae through the cylinders by measuring the pressure difference between both sides of them. Therefore, without using tracer gas, which is indispensable in measurements on site, the outflow-inflow rate can be determined accurately. The ventilation performance of multiple rooms, which normally requires technical expertise in the multi-tracer gas technique, can be determined precisely.

Efficiently utilizing the advantages of the test equipment above, the tests were conducted for 60 cases combining three parameters: the airtightness of the cylinder house as listed in Table 1 (five levels), the size of the internal door undercut from Table 2 (three sizes), and the internal-external temperature difference from Table 3 (four levels).

The airtightness levels shown in Table 1 were achieved by varying the number of opened cylinders in the envelope of DK, LV, BS, and BN. The cylinder opening patterns are illustrated in Figure 3. With all the opening patterns, the cylinders were arranged symmetrically with respect to the middle of the floor-to-ceiling height. Airtightness Levels 1 and 2 represent highly insulated and airtight buildings including single-family houses and reinforced concrete condominiums. Airtightness Levels 3 to 5 correspond to middle-grade airtight houses, and level 10 corresponds to leaky houses.

"U.C. 50 mm" diameter in Table 2 represents the crack around the door without intended undercut. "U.C. 160 mm" diameter and "U.C. 200 mm" diameter mean a difference of intended undercut size. If the Cd (discharge coefficient of opening) of the rectangular undercut is assumed to be 0.7, U.C. 160 mm and 200 mm diameters are equivalent to undercuts 2.8 cm and 4.6 cm high, respectively, in a 70 cm wide door.

The internal-external temperature differences in Table 3 were produced by controlling the temperature of the cylinder house and that of the artificial climate chamber, the latter corresponding to the outside temperature. Under almost all of the test conditions, the control accuracy was satisfactory with the temperature difference within the target 0.5°C. However, when the target T was 0 K, the internal-external difference was actually 2 K, since it is difficult to achieve the condition T=0 K.

The exhaust fan for the ventilation system was located in DK (see Figure 2). The rotation speed of the fan was controlled by an invertor so that the exhaust rate by the fan was as close as possible to 88 m^3/h (air change rate 0.5/h for the whole house).

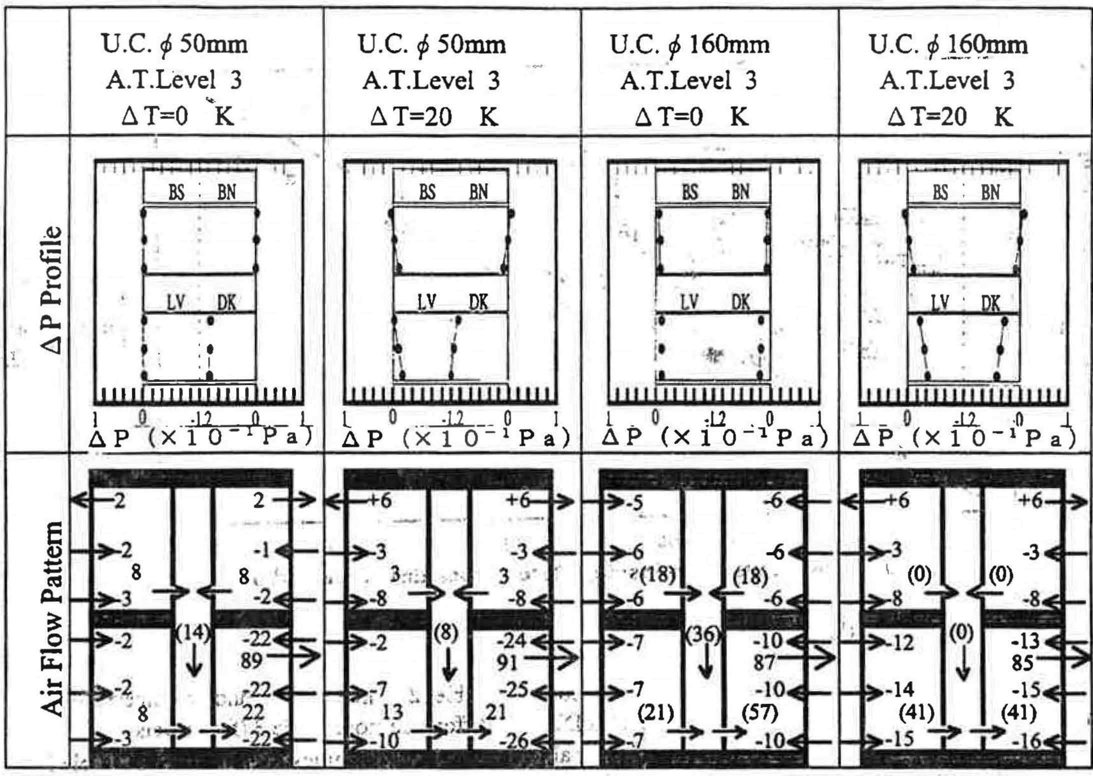

Figure 5 *Typical airflow pattern and pressure difference profile (comparison about door undercut (U.C. ϕ) and temperature difference (ΔT).*

The airflow through the envelope was calculated from the measurements by 12 pressure differential gauges installed in the envelopes and the P-Q characteristics of the cylinders given below. When calculating the flow rate, the air volume is normalized in terms of internal temperature.

$Q = 7.11 \quad \Delta P^{1/2}$ (Inflow, measurement condition: air temperature=21.0, relative humidity=65%, atmospheric pressure=1007.5 hPa)

$Q = 7.25 \times \Delta P^{1/2}$ (Outflow, measurement condition: air temperature=19.9, relative humidity=64%, atmospheric pressure=1018.2 hPa)

Unit: Q (m^3/h) P (Pa)

EXPERIMENTAL RESULTS (RAW DATA)

For the purpose of verifying the accuracy of the measurements, the balances of outflow-inflow across the envelope under every test condition are plotted in Figure 4. Under almost all test conditions, the variation of the balance is within 5%. This shows the satisfactory accuracy of the flow rate measurements. The measured values that deviate significantly from 5% are for those cases with a low airtightness and T=0 K, which can be attributed to the fact that the accuracy of the pressure gauge becomes lower with the decrease of outside-inside pressure difference. In the succeeding figures, the four measurements with poor accuracy are omitted.

Using as an example the airtightness Level 3, Figure 5 illustrates a comparison between the cases with U.C. 50 mm and 160 mm diameter at T= 0 and 20 K. The upper row shows the pressure difference profiles and the lower row shows the airflow patterns. The upper portion and lower portion of each diagram for the pressure difference represent the second floor and first floor, respectively. Locating the zero reference point of indoor-outdoor pressure difference at the envelope, the plots inside the house mean the inside is negatively pressurized against the outside, while the plots outside the house mean the inside is positively pressurized against the outside. The flow patterns in the lower rows were obtained by calculating the inflow-outflow rates from the pressure differential measurements given in the upper row. The arrows pointing to the outside represent the outflow (+), while the arrows pointing to the inside show the inflow (−). The arrows in the middle of each diagram express the airflow in SC. If the planned ventilation by the exhaust fan installed in DK is achieved, the arrow in SC points downwards from the second floor to the first floor. The arrows between the four rooms and SC show the air flow through the door undercut-simulating cylinders. These flow rates were measured by four differential pressure gauges. It should be noted, however, that it was difficult to measure the pressure difference accurately because the difference across the cylinders was so little for U.C. 160 mm and 200 mm diameters, except for U.C. 50 mm diameter. Accordingly, the flow rates through the undercuts of 50 mm diameter were calculated from the pressure measurements and for the other undercut diameters, estimated values are given in parenthesis. The estimation of the airflows through the undercuts and in SC was done as follows. First, the airflows through the undercuts between DK-SC and LV-SC were calculated from the flow balances through the envelope of DK and LV. Then, from the flow balance through these two undercuts, the flow in the second floor was obtained on the basis of the flow in the first floor through SC, and vice versa. Finally, the flow rate through SC was halved. The halves were deemed as the flow through the undercut between BN-SC and between BS-SC.

From the pressure difference profiles given in the upper row of Figure 5, it is known that when the airflow resistance of the inner door is too great (U.C. 50 mm diameter), the exhaust fan does not exert significant influence upon the rooms other than in the DK where it is installed. Especially at T = 0 K, the inside-outside pressure difference is almost zero, causing almost no fresh air supply, as shown in the airflow pattern in the lower row, since there is no inside-outside temperature difference. When T = 20 K, under the influence of a relatively large inside-outside temperature difference, fresh air flows in through the lower position of each room in the second floor, while inside air escapes through the upper position. This phenomenon is called "one room circuit." As shown by these patterns, when the airflow resistance of the inner door is too high, the pressure profile at six points, including three points in the first floor and three points in the second floor, respectively, is not on a single straight line. Consequently, more than one neutral plane may exist in a house with conditions similar to the case shown in Figure 5. Whether or not the pressure profile at six points in LV and BS, where no fan is installed, forms a single straight line is considered in the following discussion to be a criterion for judging whether or not a single-zone state is established.

The pressure differential profiles demonstrate that when intended undercuts (U.C. 160 mm diameter) are provided, the exhaust fan effectively exerts influence upon all the rooms. Especially when T = 0 K, the fresh air supply to different rooms is approximately equal, and satisfactory ventilation may be available with a single exhaust fan, as shown by the airflow pattern in the lower row of Figure 5. When T = 20 K, the inside of the house is in a nearly single-zone state due to the provision of suitable undercuts. The pressure difference profile at six points from the vicinity of the second-floor ceiling to the first-floor surface is approximately on a single straight line. Such a pressure profile is achieved by superposition of the exhaust fan effect on the buoyancy-induced ventilation (or infiltration) in a single-zone house where fresh air flows in from the first floor and inside air flows out from the second floor. A large amount of fresh air flows into DK and LV, while inside air escapes from the upper portion of BN and BS (one room circuit).

Particular Airflows

We have observed the airflows in a one-room circuit in Figure 5. Figure 6 shows two specific airflows that were obtained by tests with U.C. 160 mm diameter, T= 20 K, and airtightness levels of 5 and 10. With an airtightness level of 5, since 65 m^3/h of fresh air flows in first-floor DK and 58 m^3/h in first-floor LV, the portion of fresh air inflow into LV that cannot be evacuated by the exhaust fan in DK rises under the buoyancy effect in the staircase and flows into the second-floor BN and BS, as shown from the upward arrows in SC in the middle of Figure 6. This phenomenon is hereinafter referred to as "Phenomenon 1."

At the airtightness level 10, fresh air flows in DK at a rate of 114 m^3/h and in LV at a rate of 81 m^3/h. The portion of fresh air not evacuated by the fan from DK flows into BN and BS, hereinafter referred to as "Phenomenon 2."

These phenomena can be explained as follows. In a house with a low airtightness level, there is a great overall area of cracks in the envelope. The flow resistance through the fan is, therefore, small and a large volume of fresh air, exceeding the exhaust capacity of the fan, flows into the first-floor DK and LV, which become the inflow side because of ventilation due to buoyancy. The indoor environment is deteriorated by these phenomena. For example, water vapor, bad odor, smoke, etc., enter into the second-floor rooms that should be kept clean, causing water vapor condensation and worse air quality. The following description considers in further detail these particular airflows (one room circuit, reverse flow Phenomena 1 and 2), which are opposite to the airflow plan of the exhaust-only ventilation system without duct.

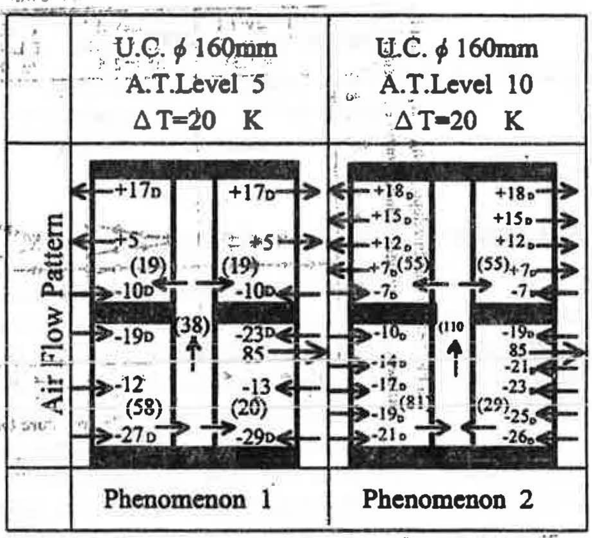

Figure 6 Uncontrollable airflow pattern.

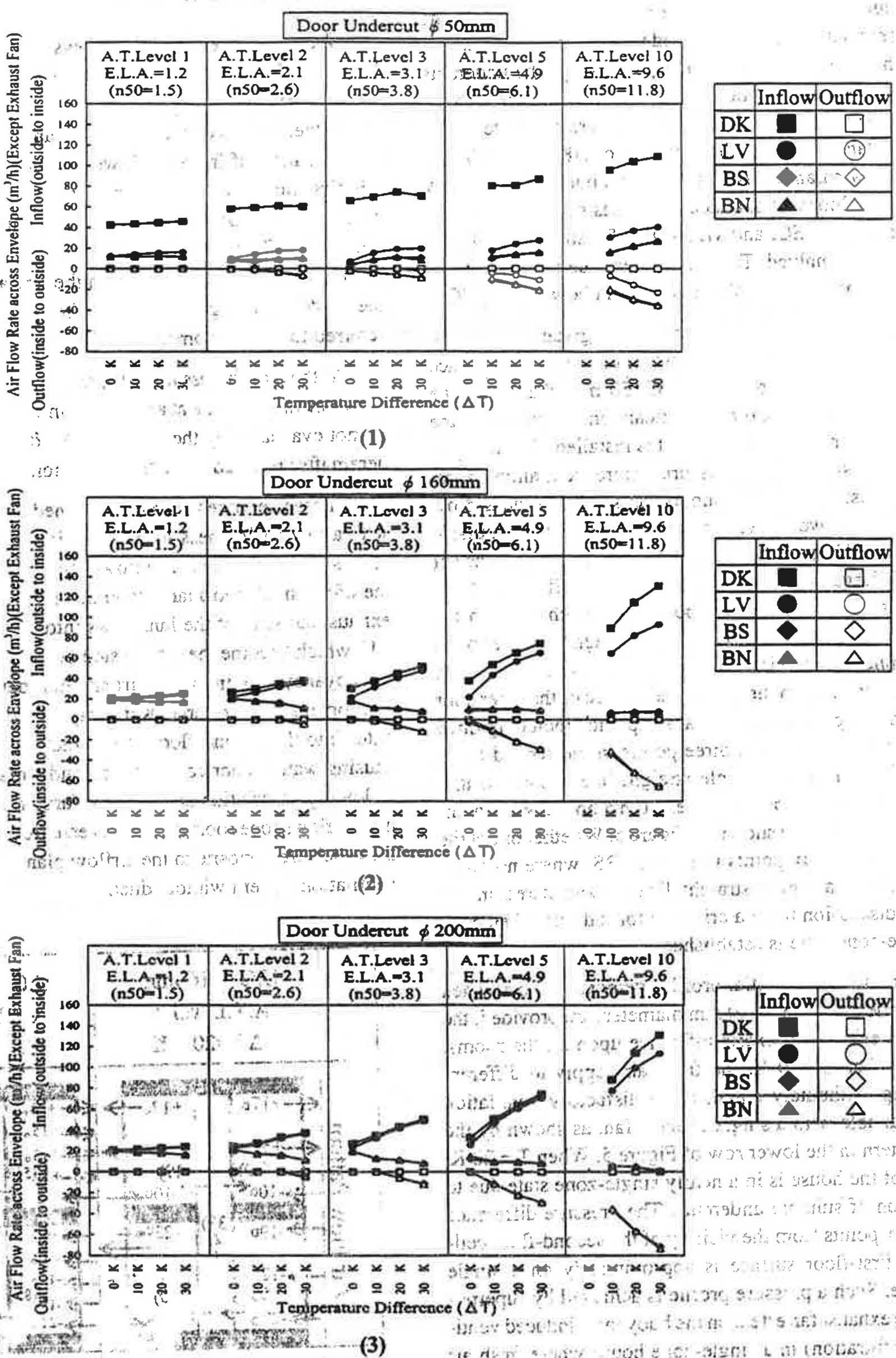

Figure 7 Airflow rate across envelope depending upon airtightness (ELA) and ΔT.

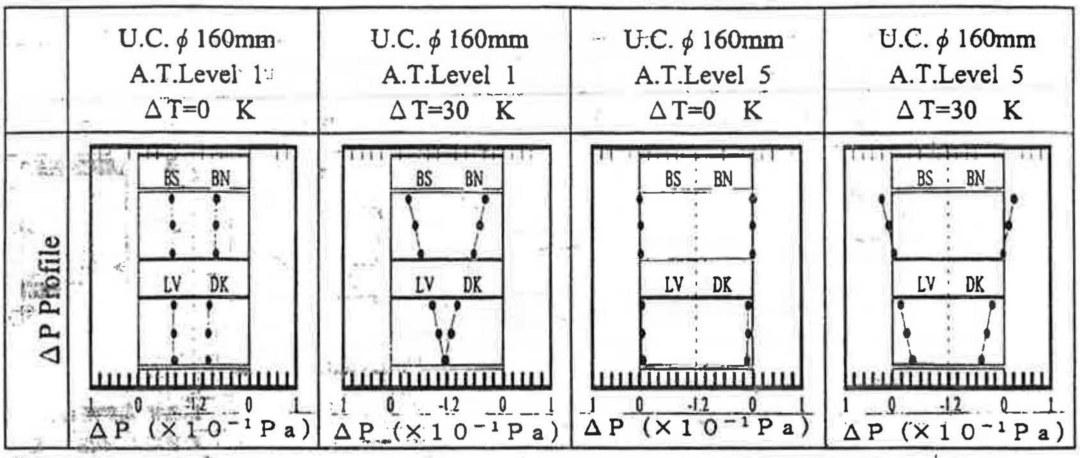

Figure 8 Comparison of pressure difference profile depending upon A.T. level and ΔT.

SYSTEMATIC COMPARISON OF INFLOW AND OUTFLOW RATES

Figure 7 shows the plots of varying inflow and outflow ratios in the living rooms of the experimental house designed with a nonduct exhaust-only ventilation system. The three sets of graphs show a systematic comparison, with U.C. 50, 160, and 200 mm diameter, respectively, of the influence upon the airflow rate exerted by the airtightness of the house and the internal-external temperature difference. The black symbols in the positive range of the ordinate represent the fresh air supply rate through the envelope of each room. If the exhaust fan in DK provides the same effect to each of the four rooms, the fresh air infiltration is about 20 m^3/h in every room. The white marks in the negative range of the ordinate represent the outflow rate of each room through the envelope. When the outflow rate is negative, the "one room circuit" mentioned in the preceding section occurs. Each set of four plots linked with a line shows the variation of the outflow-inflow rate, fixing the airtightness and changing the internal-external temperature difference. Considering that the internal temperature is nearly constant, if the four plots on a line do not fluctuate significantly (three plots when the data of outflow-inflow balance in Figure 4 are not satisfactory), stable ventilation can be achieved and is hardly affected by the change in external temperature.

With U.C. 50 mm diameter (no intended undercuts), the resistance through the inner door of DK is too great, a significant extracting effect of the fan is limited to DK, without ensuring required fresh air supply to the other rooms. Under the influence of a too large resistance through the internal wall and temperature difference (buoyancy), at the airtightness levels 5 and 10, inside air flows out from the first-floor LV too,

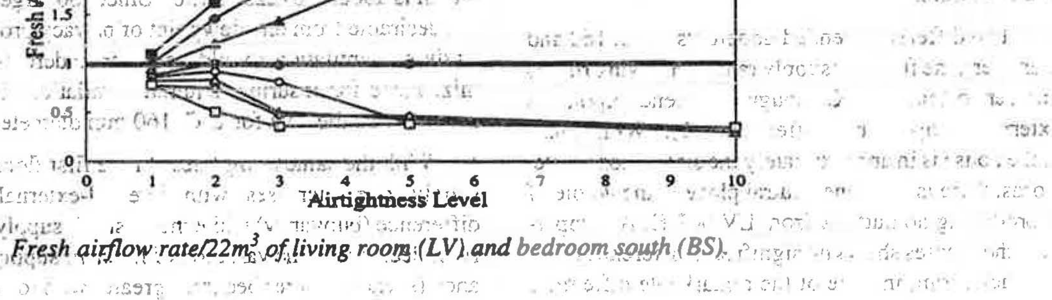

Figure 9 Fresh airflow rate/22m³ of living room (LV) and bedroom south (BS).

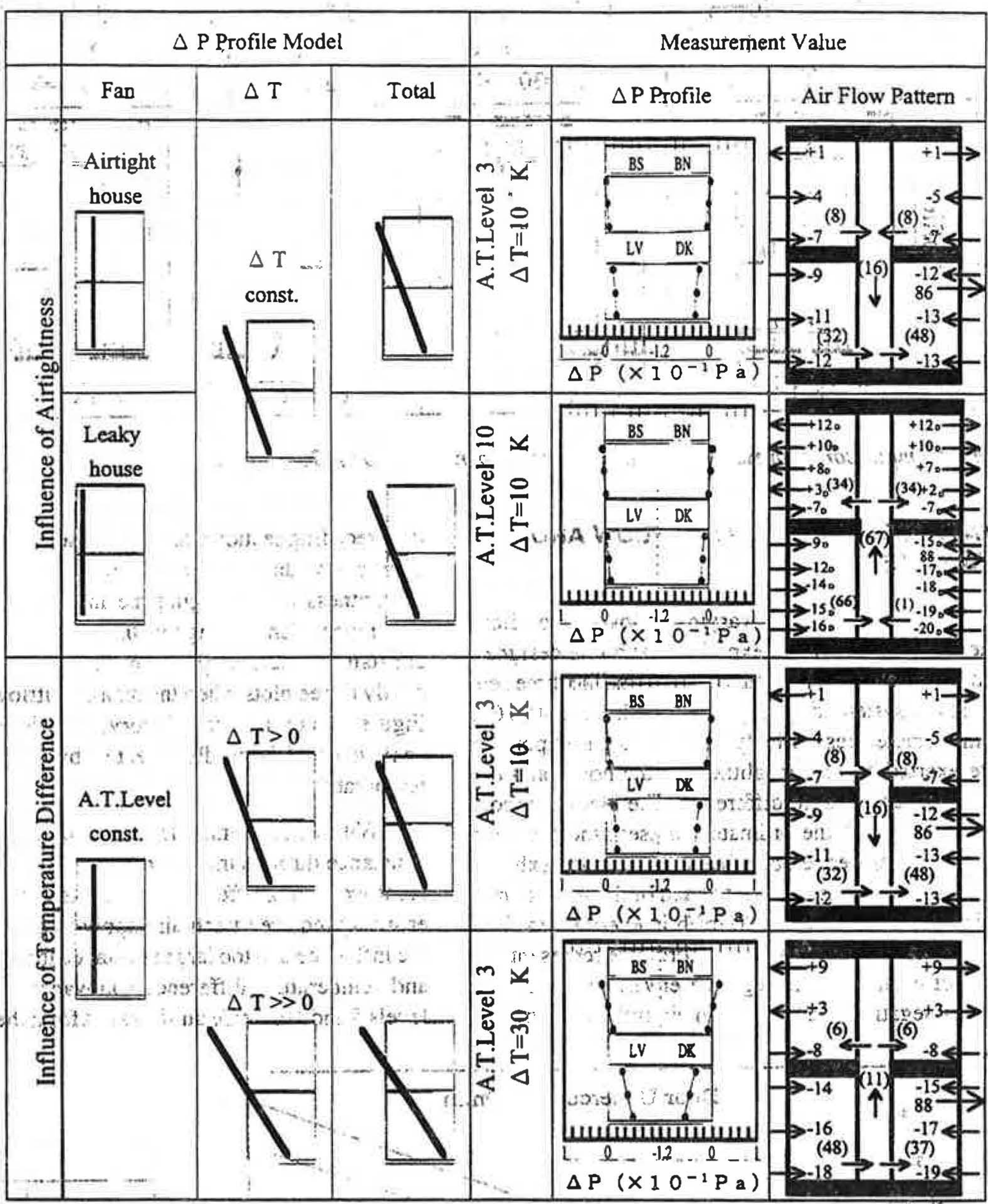

Figure 10 Movement of neutral pressure level depending upon airtightness and temperature difference.

from which it is known that a neutral plane appears both in the first and second floors.

With the two different intended undercuts (U.C. 160 and 200 mm diameter), the fresh air supply rate in the living rooms becomes nearer to that in DK, though it depends upon the internal-external temperature difference (T). With these undercuts, the house is in approximately the single-zone state. In other words, there is only one neutral plane in the whole of the house, producing no outflow from LV or DK. A comparison between these cases shows no significant difference in the flow rate in each room, in spite of the remarkable difference in the effective opening area of the undercuts, the ratio of which is about 1.6 (223 to 136). Since too large undercuts are not desirable from the viewpoint of privacy protection, etc., a study of ventilation should consider undercuts of the minimized size for ensuring required ventilation. The discussion below treats the data for U.C. 160 mm diameter.

With the same airtightness in the first floor, the fresh air supply rate increases with internal-external temperature difference (buoyancy) while the fresh-air supply in the second floor decreases. The variation of fresh air supply due to buoyancy (stack pressure) becomes greater with lowering airtightness. Such outflow-inflow behavior for typical pressure difference profiles with U.C.160 mm diameter can be clearly seen in Figure 8. Two diagrams on the left in Figure 8 represent the airtightness Level 1 at T = 0 K and 30 K and the diagrams in the right represent the airtightness Level 5 at the same Ts. When the temperature difference is zero, the exhaust fan effect can be observed separately and the pressure imbalance is great for airtightness Level 1, while it is almost zero for airtightness Level 5. Nevertheless, also for airtightness Level 5 (Figure 7), the fresh air supply rate due to the very small pressure difference is considerable except for the two rooms in the second floor. Thus, the fresh air supply rate is the same for both airtightness levels at T = 0 K, as shown in Figure 7. An essential difference between the two levels is that the fresh air supply is ensured at the higher airtightness level by a greater internal-external pressure difference and a lesser crack area, whereas it is provided at the lower airtightness level by smaller internal-external pressure difference and a greater crack area. At T = 30 K, the results are affected by both an internal-external pressure difference produced by the exhaust fan and buoyancy with airtightness Level 1, where a greater pressure difference is maintained by the exhaust fan, and the upper indoor portion of the second floor also is kept negatively pressurized against the outdoor. In the case of airtightness Level 5, air flows out from the upper portion of the second floor. These results demonstrate that the fresh-air supply rate is affected by the superposition of internal-external pressure imbalance produced by the exhaust fan on the gradient of the pressure profile due to temperature difference as well as the overall area of cracks in the building fabric.

It is clear from Figure 7-2 for U.C. 160 mm diameter that at airtightness Level 1, fresh air is supplied at approximately the same rate to each room, regardless of the magnitude of T, and at any internal-external temperature, one room circuit is not generated. This may be attributed to the fact that there is only one crack-simulating cylinder opened at the middle height of each room. However, if the effective opening area of each cylinder was divided into two equal halves, and those two halved cracks (cylinders) were arranged in the same positions as in the case of Level 2 (See Figure 2), air outflow would not occur in spite of the existence of a crack near the second-floor ceiling, as inferred from the pressure profile at airtightness Level 1 and T = 30 K (See Figure 8).

One room circuit in reverse of the planned airflow direction is found in almost all cases at lower airtightness Levels 5 and 10, and at the Levels 2 and 3, the internal-external temperature difference is great.

The discussion above has referred to both outflow and inflow. We will discuss the analytical results exclusively regarding the inflow of fresh air into each room from the viewpoint of supplying a required fresh-air volume. The cases with U.C. 160 mm diameter alone are studied below.

Figure 9 shows the plots of the fresh-air supply rate to LV and BS divided by 22 m^3/h, which is the target fresh-air supply per room, determined on the assumption that the effect of mechanical extract at a rate of 88 m^3/h is distributed uniformly to the four rooms. The data for DK and BN are excluded from the figure because the exhaust fan permanently supplies a fresh-air supply exceeding the target in DK, and the supply in BN is similar to that in BS. The black symbols representing LV show fresh-air supply rates exceeding the target under every condition. In contrast, the white symbols for BS represent the fresh-air supply rate that is below the target in almost all cases.

At the same airtightness level, the fresh-air supply rate in the first-floor LV increases and the fresh-air supply rate in

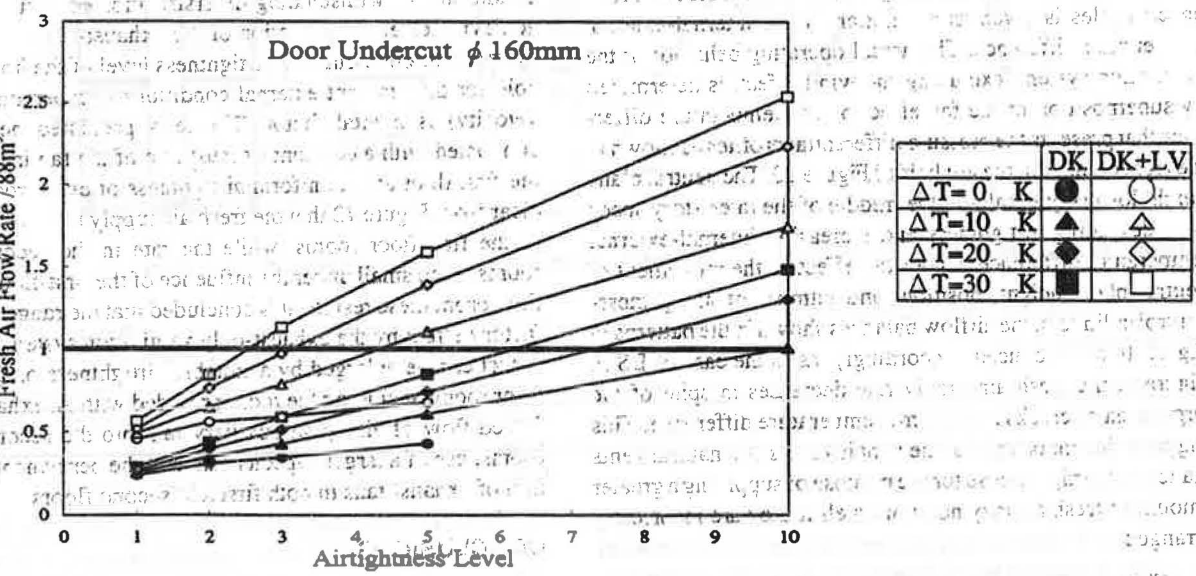

Figure 11 Fresh airflow rate/88 m^3 of dining kitchen (DK) and living room (LV).

second-floor BS decreases due to the buoyancy effect, with increasing internal-external temperature difference. When the buoyancy alone is considered with a constant internal-external temperature difference and lowering airtightness level, the overall area of cracks becomes larger, leading to augmentation of the fresh air supply rate. However, for the exhaust-only ventilation system without duct, it is essential to note the variation of the neutral plane location in the envelope under the superposed effect of the pressure difference produced by the exhaust fan and by the temperature difference. For illustrating the neutral plane movement (Awbi 1991), simplified pressure profile models, measured pressure profiles, and airflow patterns are shown in Figure 10.

In the upper half of Figure 10, the variation of the neutral plane is depicted at a constant temperature difference and at different airtightness levels, while in the lower half, the variation is depicted at a constant airtightness level and different temperature imbalances. The left columns show model diagrams and the right columns show pressure difference profiles and airflow patterns based upon measurements. In the model diagrams, the left column illustrates the pressure difference profiles produced by the exhaust fan. In an airtight house, greater internal-external pressure difference is generated by the fan, and in a leaky house, a smaller internal-external pressure difference is generated. In the center column in the left half of Figure 10, pressure difference profiles caused by a temperature difference are given. When proper undercuts are provided, a nearly single-zone state occurs and cracks are distributed symmetrically about the space between the first-floor ceiling and the second floor (inter-story space). The pressure difference profile forms a single straight line and the neutral plane is at the middle of this space or at the symmetry axis of the crack arrangement (the inter-story space is not depicted in the diagrams). The gradient of the pressure difference profiles is given as a function of the internal-external temperature difference. The actual operating behavior of the ventilation system, excluding the wind effect, is determined by superposition of the fan effect on the temperature difference that presents the pressure differential profiles as shown in the right column in the left half of Figure 10. The neutral plane height lowers gradually to the middle of the inter-story space with degrading airtightness and increasing internal-external temperature difference. Under the effect of the movement of neutral plane height, position, and number of airtightness-control cylinders, the airflow balances shown in the patterns in Figure 10 are produced. Accordingly, as in the case of BS in Figure 9, the fresh air supply rate decreases in spite of the larger area of cracks at the same temperature difference. This suggests the importance of the vent layout, since natural vents made in an airtight house for the purpose of supplying a greater amount of fresh air may not work well if they are incorrectly arranged.

Figure 11 shows the variation of the fresh air supply in DK and DK+LV divided by 88 m^3/h, which is the capacity of the exhaust fan. When the ordinate exceeds 1 for DK, airflows from DK to BN and BS ("Phenomenon 2") occur (see Figure 6). When the ordinate is more than 1 for DK+LV, air flows from LV to 2F rooms ("Phenomenon 1") (see Figure 6). In Figure 11, it is shown that "Phenomenon 2," which departs most remarkably from the projected ventilation flow, occurs at the airtightness Level 10 with a temperature difference of 10 K or more. "Phenomenon 1" occurs at the airtightness Level 3 with a temperature difference of 30 K and at the airtightness Levels 5 and 10 with a temperature difference of 10 K or more.

Figure 12 shows contour maps of the fresh air supply rates in DK, LV, and BS normalized in terms of 22 m^3/h. Excessive fresh air supply in LV, as shown in Figure 9, is inconvenient for heating energy saving, while too little supply is not suitable for maintaining good air quality. For this reason, the regions covering 0.5 to 1.5 times the target supply are shaded in Figure 12.

If the shaded ranges in Figure 12 are assumed to be a condition for ensuring satisfactory ventilation, the contour map for DK is the least advantageous since it has the smallest shaded range among the three rooms. At airtightness Level 1, temperature differences from 0 to 30 K satisfy the ventilation requirement. At Level 2, temperature differences of 15 K or less satisfy the ventilation requirement, and at Level 3, 4 K or less meet the requirement.

If a rate of more than 0.5 times the target fresh air supply is assumed satisfactory for the purpose of providing the minimum ventilation rate for maintenance of good air quality, all the conditions in DK and LV meet the requirement while the satisfactory range for BS is the smallest. In BS, at airtightness Levels 1 and 2, temperature differences from 0 to 30 K meet the requirement; at Level 3, 20 K or less meets the requirement; and at Level 4, 10 K or less satisfies the requirement.

There are various definitions of a satisfactory ventilation condition. Notwithstanding diversification of definition, for achieving effective operation of the exhaust-only ventilation system without a duct, an airtightness level of the house suitable for the ambient external conditions (temperature, wind velocity) is a vital factor. The tests presented here were conducted with a constant exhaust rate of the fan installed in the first floor and a uniform airtightness of every room. It is clear from Figure 12 that the fresh air supply rate is excessive in the first-floor rooms, while the rate in the second-floor rooms is too small under the influence of the first-floor condition. From these results, it is concluded that the range of satisfactory effect by the exhaust-only ventilation system without a duct can be enlarged by a suitable airtightness of the first-floor rooms including the room provided with an exhaust fan, forced flow of air by an auxiliary fan into the second-floor rooms, use of a larger capacity fan, and the permanent operation of exhaust fans in both first and second floors.

CONCLUSIONS

The following have been verified through the study discussed in this paper.

- If appropriate undercuts are provided in highly airtight

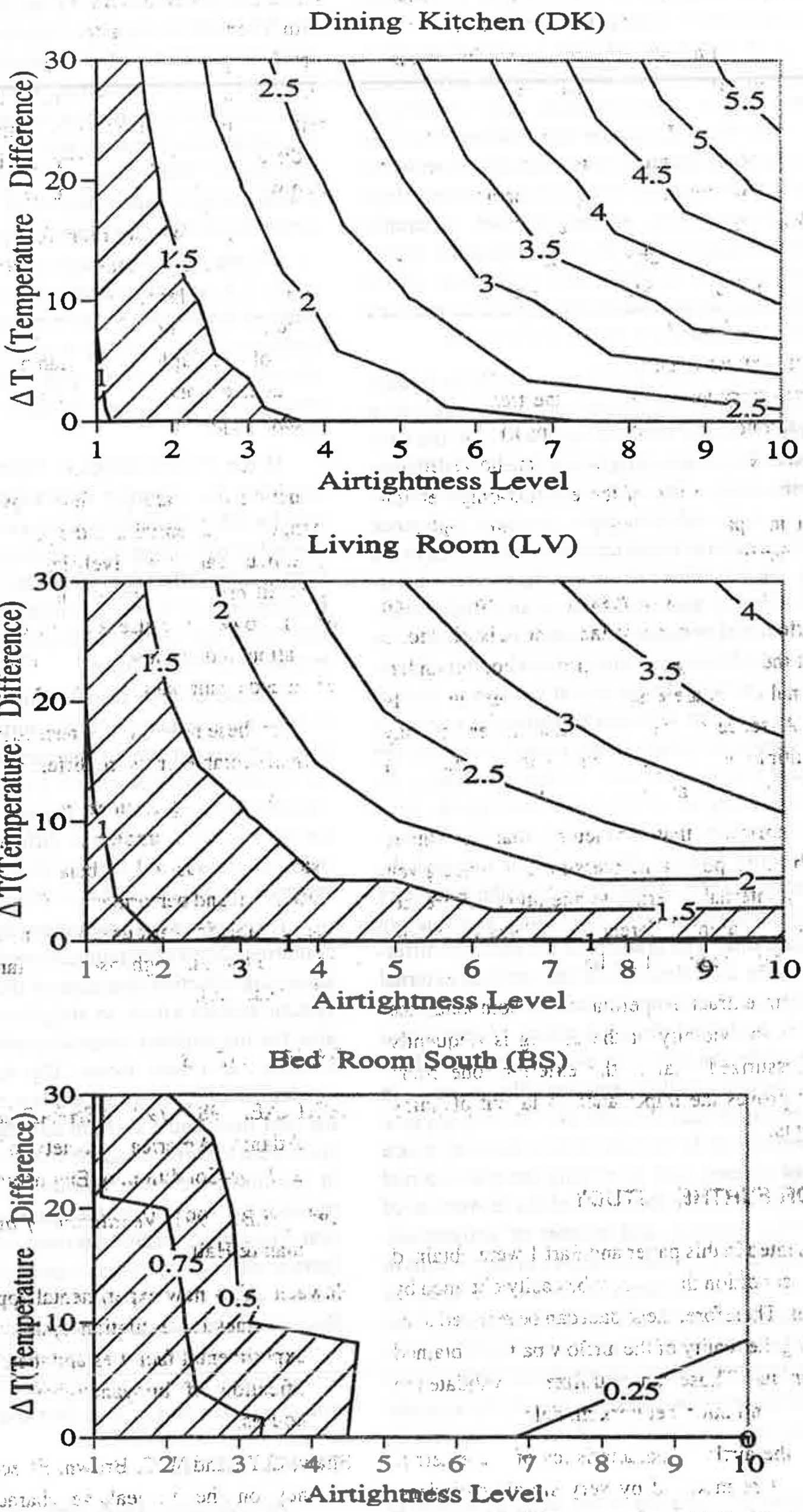

Figure 12. Fresh airflow rate/22 m^3 (target volume).

houses (airtightness Levels 1 and 2), the nonduct exhaust-only ventilation with a single exhaust fan is capable of performing stable ventilation almost independently of outside temperature change.

- In houses of middle airtightness, Levels (3 to 5), with very low outside temperatures in winter, the exhaust-only ventilation without a duct may not operate satisfactorily. Leaky houses (airtightness Level 10) are not suitable for this ventilation scheme since the fan does not produce a significant negative pressure because of a great overall area of cracks.
- When the air extract is performed solely from the first floor in a two-story leaky building, the fresh air supply rate in the second floor tends to be insufficient due to the buoyancy ventilation. This suggests, however, the possibility of effective use of the exhaust-only ventilation system in apartment houses (flat plan) and one-story single-family houses.
- When the flow resistance across internal doors is too great, the effect of the exhaust fan is not distributed to the whole of the dwelling unit. Therefore, correct undercuts in internal doors are essential for the exhaust-only ventilation. Absence of the appropriate undercuts may generate multiple neutral planes under the influence of internal-external temperature differences.
- The tests reconfirmed that the neutral plane height is determined by superposing the pressure difference given by the fan by internal-external temperature difference. Increase of temperature difference and decrease of airtightness lower the neutral plane height.
- Even if the air extract is permanently complete, the indoor zone in the vicinity of the ceiling is frequently positively pressurized against the exterior (one room circuit). This proves the importance of layout planning of natural vents.

PROSPECT FOR FURTHER STUDY

The data presented in this paper and Part 1 were obtained in the steady-state condition that cannot be easily obtained by field investigations. Therefore, these data can be referred to as a basis for verifying the reality of the airflow pattern obtained by tracer gas technique. Those can be utilized to validate the result of multizone ventilation network models.

In this study, the airflow characteristics of the external and internal walls were modeled by very simple cylinders. This technique does not distinguish cracks in building envelopes (P-Q characteristics with an exponential factor of about 1/1) from simple openings such as vents (P-Q characteristics with an exponential factor of about 1/2). In future studies, by simulating more faithfully the states where cracks of different airflow characteristics exist, actual conditions will be reflected more precisely on experiments. By discerning cracks of different fluid-dynamic properties, ventilation and infiltration will be determined separately.

One possible solution for preventing pollutants from spreading is the permanent operation of a fan both in the bathroom, where a large amount of water vapor is produced, and in the lavatory. For this purpose, it is necessary to study the effect of a multiple exhaust fan permanently operated and the mutual effect between a permanently operated fan and intermittently operated fan.

For achieving an exhaust-only ventilation system without a duct that is hardly affected by the outside temperature change, it is essential that the pressure difference provided by the exhaust fan be relatively larger than that due to the temperature difference. Excessive internal-external pressure differences, however, cause adverse effects, such as less smooth operation of door or windows in the envelope, noise (whistle) produced by air passing through cracks around windows, etc.

For these reasons, it is necessary to know the upper limit of an acceptable pressure difference.

After finding engineering solutions for these problems, the authors will implement further study on ventilation systems (exhaust-only, balanced ventilation, and natural ventilation) and performance of houses (airtightness, undercut size) suitable for various types of residential buildings (single-story buildings, high-rise multifamily houses, three-story buildings, etc.).

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