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Airtightness and Ventilation Strategy in Japanese Residences

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SUMMARY

In this paper, the relationship between airtightness and indoor air quality is shown, based on measurements made of thirteen detached wooden houses. Secondly, a chart for predicting air infiltration from airtightness rank is given, and the relationship between airtightness and air infiltration is discussed. Finally, optimum combinations of heating and ventilating systems and types of cooking appliances are suggested according to the airtightness rank of a house.

1. INTRODUCTION

In recent years, the degree of thermal insulation and airtighness of newly constructed houses has greatly increased. In airtight houses, with a low level of air infiltrating from outdoors, air pollution may become a problem; thus it is necessary to select heating equipment which does not expel the exhaust into the room, and to install an optimum ventilating system.

The purpose of this paper is to propose optimum combinations of heating and ventilating systems and types of cooking appliances according to the airtightness rank of a house, on the basis of the relationship between airtightness and indoor air quality as well as the relationship between airtightness and air infiltration.

About sixty years ago, Nomura [1] and Ohtani [2] measured, for the first time, the amount of cracks in room envelopes by means of a scale, and investigated the effect of these cracks on air infiltration. By 1950 a theorem representing the air infiltration mechanism, taking into account both wind and buoyancy effects, was formulated by Watanabe [3] and Shoda [4]. A circuit network calculation method for measuring air infiltration in a multi-room building was devised by Maeda [5].

Since approximately 1960, unvented portable oil heaters have become popular for heating houses. In 1964, Yoshizawa [6] began research on the air quality and ventilation requirements of rooms heated by such means. After the advent of construction of concrete, uninsulated, multi-family houses, problems with condensation became a serious concern. Maeda *et al.* [7] therefore conducted a detailed investigation of the thermal environment and air quality of such apartments in 1957. Initially, they measured the airtightness of building components using the fan pressurization technique. Subsequently, in 1969, Shoda *et al.* [8] proposed construction methods for preventing condensation based on the results of a detailed investigation of room temperature, humidity and lifestyle of occupants in concrete apartments. Air infiltration research for the purpose of energy conservation has only been carried out in the last ten years and the airtightness of various types of houses has only been measured by researchers since 1982. Murakami and Yoshino [9] reported on the airtightness of residential buildings in Japan at the fourth Air Infiltration Conference in 1983.

2. AIRTIGHTNESS AND INDOOR AIR QUALITY OF NEWLY CONSTRUCTED HOUSES

This chapter discusses the measurement results of airtightness and indoor air quality for thirteen occupied wooden frame houses recently constructed by three different home builders in Sendai city.

2.1. Description of houses measured and measurement period

Table 1 describes the houses measured. These houses were constructed between 1981 and 1984. All houses have thermally insulated walls, ceilings and floors, except for house

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TABLE 1

Description* of measured houses

House number	Date of completion	Floor area (m^2)	Depth of insulation (cm)			Window	Heating equipment	Ventilation in living room	House builder
			Wall	Floor	Ceiling				
1	Jan. 1983	109	5	5	7.5	D.S.	Vented oil heater	Natural	A
2	Jan. 1983	105	5	5	7.5	D.S.	Unvented oil heater & "Kotatsu"	Natural	A
3	Jan. 1983	109	5	5	7.5	D.S.	Vented gas heater	Natural	A
4	Mar. 1983	110	5	5	7.5	D.S.	Unvented & vented oil heaters	Natural	A
5	Dec. 1984	109 F	10	2.5	10	D.S.	Floor heating & "Kotatsu"	Mechanical†	B
6	Sept. 1984	142 F	10	—	10	D.S.	Vented oil heater & "Kotatsu"	Mechanical	B
7	Sept. 1984	183 F	15	5	15	D.S.	Floor heating	Mechanical	B
8	Jan. 1982	110	5	5	7.5	D.G.	Vented oil heater & "Kotatsu"	Natural	A
9	Oct. 1984	152 F	5	5	10	D.S.	Floor heating	Mechanical	C
10	Mar. 1983	147 F	5	5	10	D.G.	Floor heating & "Kotatsu"	Natural	C
11	Aug. 1983	163 F	5	5	10	D.S.	Floor heating	Natural	C
12	June 1981	120 F	5	5	10	D.G.	Floor heating	Mechanical	C
13	Aug. 1981	109 F	5	5	10	D.G.	Floor heating & "Kotatsu"	Mechanical	C

*F = concrete floor is constructed. D.S. = double sashes, D.G. = double glazing. All houses have two stories except for house #13 with a flat.

†"Mechanical ventilation" means an exhaust fan unit, which is situated in an outer wall, with an air-to-air heat exchanger, except for house #13.

#6 which does not have an insulated floor. The depth of insulation in house #7, which is the most heavily insulated, is 15 cm for the walls and ceiling, and 5 cm for the floor. The houses constructed by building companies B and C have concrete floors including hot water pipes and thermal insulation under the floor, except that house #6 has no floor heating. House #2, of the houses without floor heating, has an unvented portable oil heater and an electric "Kotatsu", a traditional Japanese electric heater which is mounted under a low table. House #4 has a vented oil heater for heating the living room as well as an unvented portable oil heater for heating the dining room. A vented heater takes outside air for combustion and expels the exhaust outdoors. The other houses have vented oil heaters. Windows have double glazing or double sashes.

The periods for measurement of airtightness and indoor air quality are shown in Table 2.

TABLE 2

Periods for measurements (1985)

House no.	Airtightness	Indoor air quality
1	2/8	2/1 ~ 2/2
2	2/8	2/28 ~ 3/2
3	2/8	1/29 ~ 1/30
4	2/12	1/30 ~ 1/31
5	3/2	1/31 ~ 2/1
6	2/1	2/2 ~ 2/3
7	3/2	2/4 ~ 2/5
8	3/8	2/6 ~ 2/7
9	1/31	2/7 ~ 2/8
10	3/8	2/7 ~ 2/8
11	—	2/8 ~ 2/9
12	3/13	2/9 ~ 2/10
13	3/13	2/13 ~ 2/14

2.2. Measurement of airtightness

2.2.1. Method of measurement

There are several methods available for measurement of the airtightness of a house.

One method involves the use of a fan to pressurize or depressurize the house. Murakami and Yoshino [9] and Kamata *et al.* [10] have shown that the volumetric flow rate when a house is depressurized is a little lower than when it is pressurized at the same value of pressure difference across the building envelope. In Japan, the pressurization method is often used because the results obtained with this method reveal a house to be more leaky than with the depressurization method.

In our test, airtightness measurements were made by the fan pressurization method. Internal pressure was increased by a fan attached to a duct penetrating a thin board set in an open window. Pressure differences were measured by a capacitance manometer. Flow rate in the duct was measured by a thermistor anemometer. Measurements were carried out under conditions of low wind speed.

2.2.2. Measured results

Figure 1 shows the relationship between the pressure difference across the building envelope and the volumetric flow rate. This relationship is expressed by

$$Q = Q_r\left(\frac{\Delta p}{\Delta p_r}\right)^{1/n} \qquad (1)$$

Table 3 shows Q_r, for $\Delta p_r = 9.8$ Pa and n of eqn. (1) estimated by regression lines. The value of exponent n for house #9 was unreasonably high, more than 2.0. One of the reasons may be that the measurement was

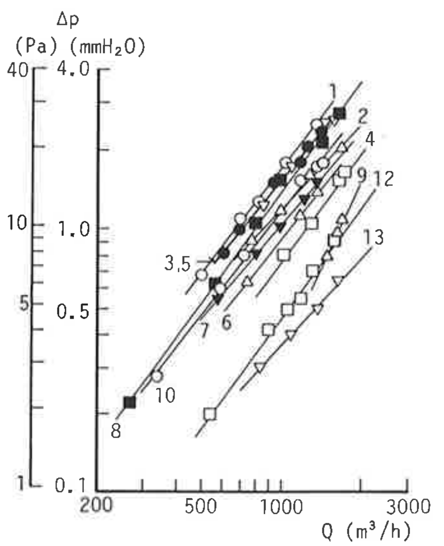

Fig. 1. Pressure difference and volumetric flow rate.

TABLE 3

Airtightness of measured houses

House no.	Q_r	n	A_r	A_r^*
1	672	1.29	463	4.24
2	845	1.07	598	5.70
3	706	1.24	500	4.61
4	1200	1.37	851	7.73
5	706	1.22	500	4.61
6	1060	1.28	748	5.27
7	973	1.18	688	3.77
8	792	1.39	560	5.10
9	1630	2.19	1150	7.56
10	882	1.30	624	4.23
11	—	—	—	—
12	1720	1.40	1210	10.17
13	2470	1.11	1750	16.08

done under a slightly high wind speed. Except for house #9, the value of n ranges from 1.07 to 1.40. Table 3 also shows the effective leakage area, A_r, for each house, which can be calculated by the following equation (see Appendix).

$$A_r = 2.78Q_r\left(\frac{2}{\rho_o}\,\Delta p_r\right)^{-0.5} \qquad (2)$$

In eqn. (2), Δp_r is given as 9.8 Pa. The effective leakage area per floor area, A_r^*, is also included in Table 3. The value of A_r^* is widely distributed from 3.77 to 16.1 cm^2/m^2.

The airtightness of house #11 could not be measured due to high wind speed despite three attempts on different days.

2.2.3. Comparison of airtightness for various houses using effective leakage area per floor area

Figure 2 shows the effective leakage area per floor area for various houses in different countries. Where the original airtightness data was not shown as A_r for $\Delta p_r = 9.8$ Pa, this data was converted, assuming $1/n = 0.6$. The original Figure is presented in ref. 9.

The houses measured in this test are plotted in rank 3 through 5 and, except for houses #12 and #13, appear tighter than the houses measured [11] in 1981 in Sendai City. The houses plotted in rank 3 are comparatively airtight among detached Japanese houses.

Among the houses constructed by company A, house #1, which has hinged windows with double panes, is the most airtight.

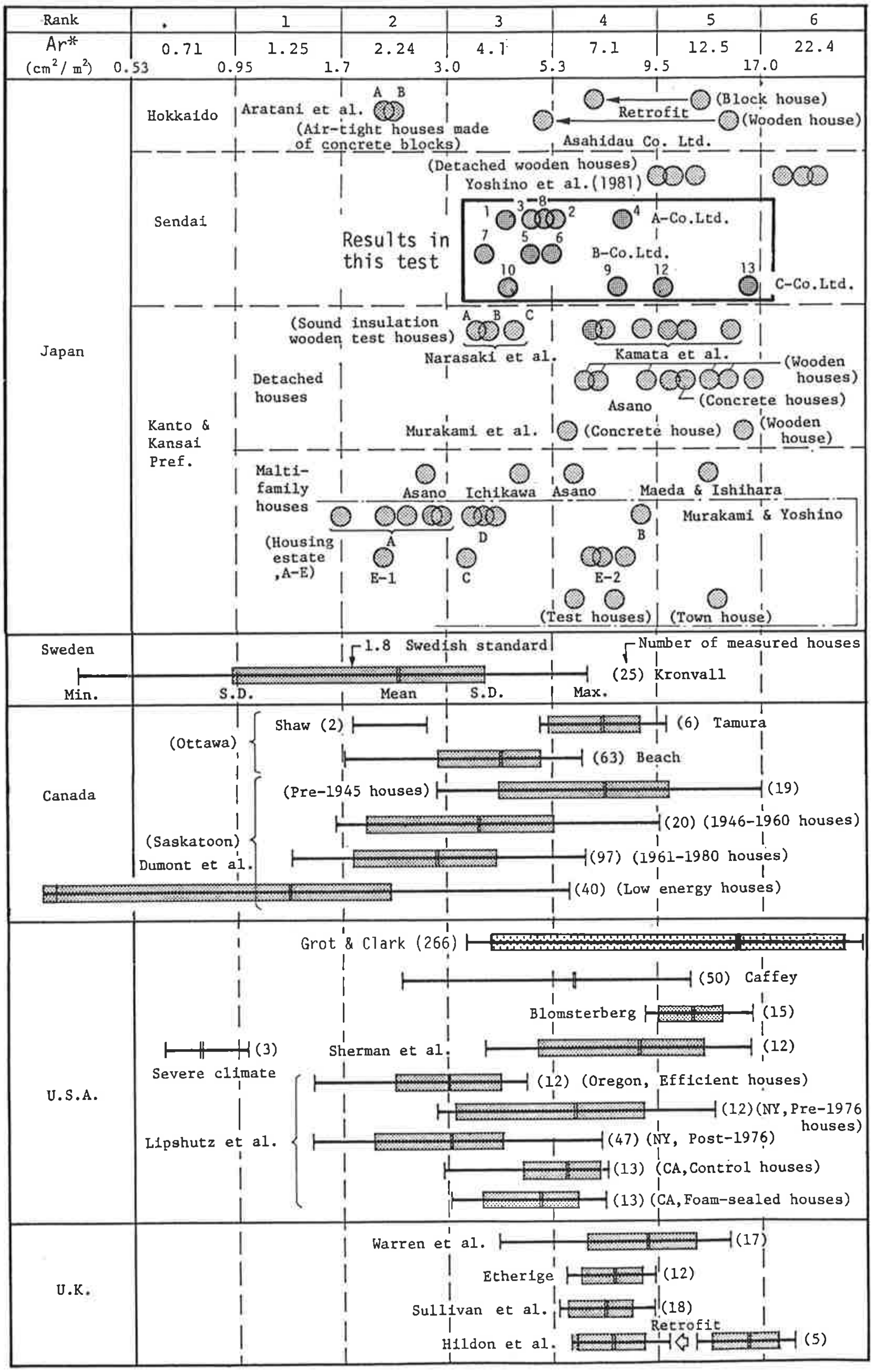

Fig. 2. Airtightness for various houses in different countries using A_r^*.

Houses #2, #3 and #4 have sliding double sashes. House #8 has hinged windows with double panes, except for the traditional Japanese room with the sliding sashes with double panes. Among the houses constructed by company B, house #7, which was constructed with airtightness in mind, is the most airtight. The airtightness of the houses constructed by company C varies greatly, House #13, plotted at the extreme right side, has sliding sashes and leaky sliding entrance doors.

House #11, in which airtightness was not tested, may be plotted between house #10 and house #9, considering the construction method and the type of windows and doors.

2.3. Measurement of indoor air quality

2.3.1. Method of measurement

The concentration of CO_2 was measured continuously for one or two days in a living room of each house by infrared analyzer. The concentration of NO_2 was measured by bare detector badges exposed for three days in a living room and a kitchen. The locations of the measurement points are shown in Fig. 3.

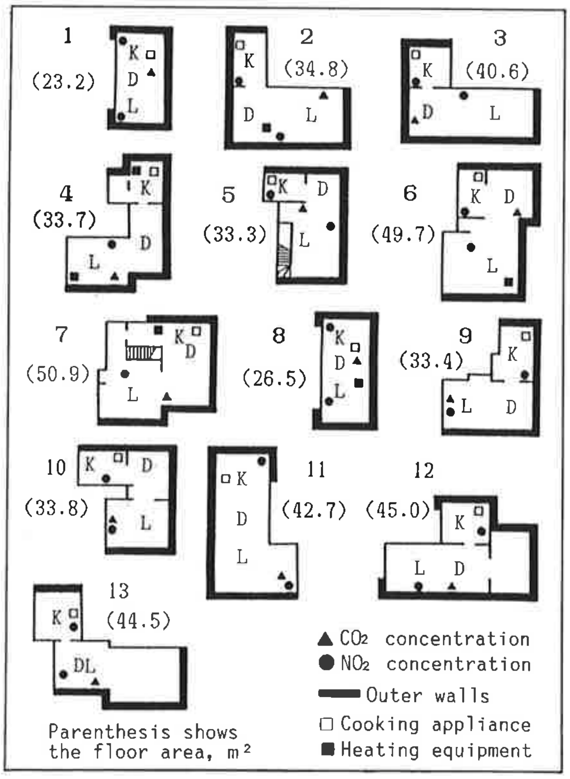

Fig. 3. Locations of measurement points for CO_2 and NO_2. K = kitchen, D = dining room, L = living room.

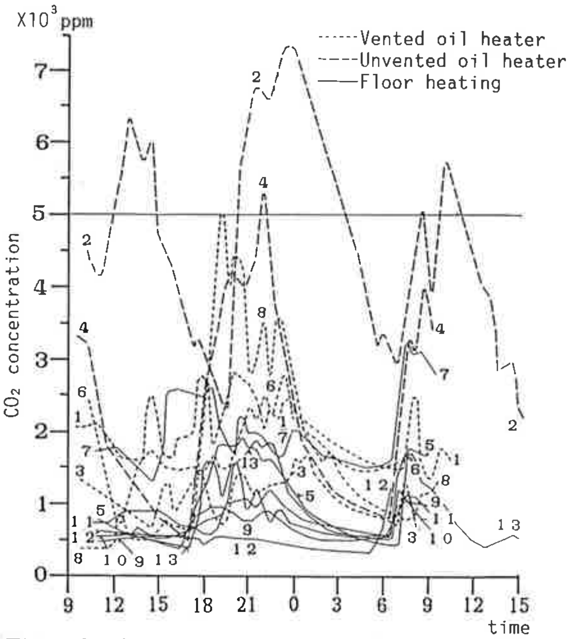

Fig. 4. Variation of CO_2 concentration.

2.3.2. Results of measurement of CO_2 concentration

Figure 4 shows the variation of CO_2 concentration measured in each house during different measuring periods. The concentration of CO_2 rises in the morning and in the evening due to CO_2 generation from occupants and cooking apparatus as well as, in some houses, from unvented oil heaters. At 21:00, the concentration is distributed from 500 to 7000 ppm. The concentration in house #2 is especially high.

Figure 5 shows the accumulative frequency distribution of CO_2 concentration during a day. In houses #1, #2, #4, #6 and #7, the CO_2 concentration is more than 1000 ppm for more than 70% of the time. In houses #1, #2

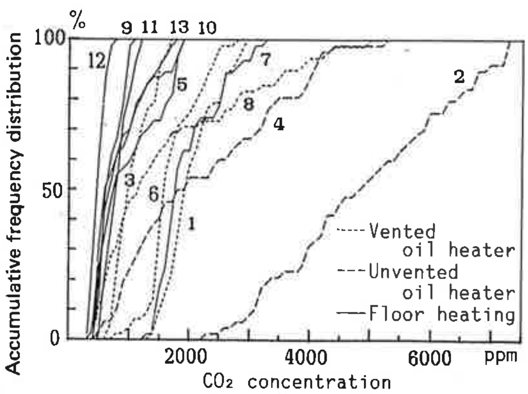

Fig. 5. Accumulative frequency distribution of CO_2 concentration.

TABLE 4

Daily mean concentrations of CO_2 and NO_2

House no.	CO_2 concentration (ppm)	NO_2 concentration (ppb)	
		Living room	Kitchen
1	1980	22	29
2	4990	470	420
3	1230	10	18
4	2240	63	49
5	980	7	12
6	1720	13	21
7	1990	11	11
8	1660	31	60
9	690	10	11
10	870	20	29
11	800	11	9
12	500	9	11
13	810	4	25

and #7, the CO_2 concentration is more than 1000 ppm all day long. Unexpectedly, the CO_2 concentration in house #2 is more than 2000 ppm all day long. Houses #2 and #4 have unvented oil heaters. Houses #1 and #7 are the most airtight among the thirteen houses measured for this test. The houses with floor heating systems, except for house #7, show a rather low CO_2 concentration. Table 4 shows the daily mean concentration of CO_2.

2.3.3. Measured result of NO_2 concentration

Table 4 shows the daily mean concentrations of NO_2 in living rooms and kitchens. The NO_2 concentration in house #2 is extremely high. The second highest is house #4. These two houses have unvented portable oil heaters. The concentration in the kitchen is higher than that in the living room, except for houses #2, #4 and #11, because the NO_2 is generated from a cooking appliance.

2.4. The relationship between airtightness and indoor air quality

2.4.1. airtightness and CO_2 concentration

Figure 6 shows the relationship between the effective leakage area per floor area, A_r^*, and a daily mean concentration of CO_2. The concentration of CO_2 is very high for houses #2 and #4 with unvented portable oil heaters. With the exception of these two houses, the

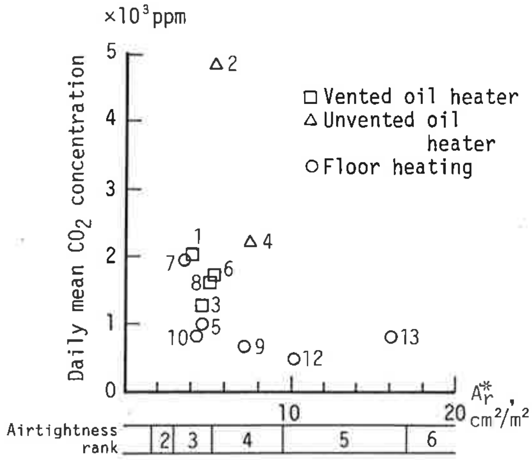

Fig. 6. CO_2 concentration and A_r^*.

CO_2 concentration in the five out of seven houses with A_r^* of rank 3 is more than 1000 ppm.

2.4.2. Airtightness and NO_2 concentration

Figure 7 shows the relationship between A_r^* and a daily mean concentration of NO_2, which is similar to Fig. 6. A strong relationship between CO_2 and NO_2 is shown in Fig. 8, in which the correlation coefficient is 0.90

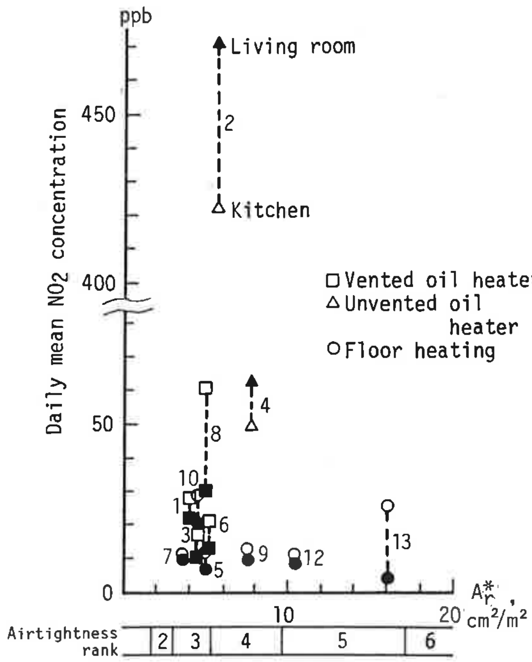

Fig. 7. NO_2 concentration and A_r^*.

3. CHART FOR PREDICTING AIR INFILTRATION FROM AIRTIGHTNESS RANK

In this Section, the calculation method for predicting air infiltration from airtightness

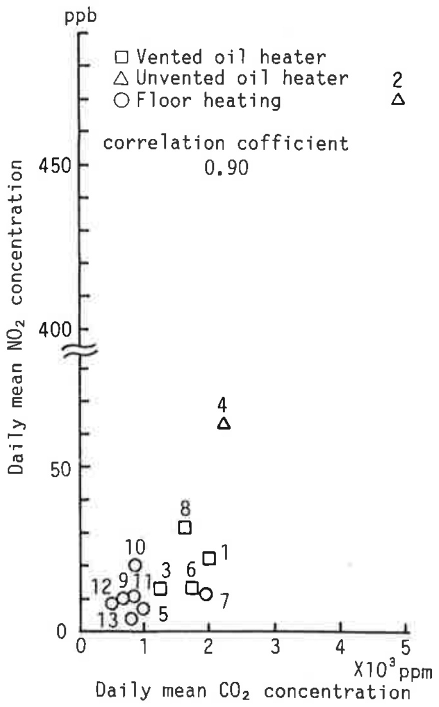

Fig. 8. Relationship between NO_2 and CO_2.

rank is shown, and the relationship between air infiltration and airtightness rank is discussed. Calculation is done for a flat with a single cell.

3.1. Calculation method

Yoshino *et al.* [12] reported that, for estimating air infiltration from the results of an airtightness test, the assumption of uniform distribution of cracks over the building envelope provided a good estimate, on the basis of a detailed field measurement of airtightness and air infiltration using three test houses.

Then, assuming uniform crack distribution, the effective leakage area of a house is divided among the four walls, the ceiling and the floor according to the area of each surface. Each wall is divided laterally into ten parts and the uniformly distributed cracks in each part are concentrated into the center of each part. For the ceiling and the floor, the cracks also are concentrated into the center of the surface.

The pressure difference, Δp_k, across a concentrated crack k at height, h_k, from the floor level, due to both wind and buoyancy effects is given as the following equation.

$$\Delta p_k = C_k\left(\frac{\rho_o}{2}\right)v^2 - p_i + gh_k(\rho_i - \rho_o) \qquad (3)$$

The air flow, Q_k, and the Δp_k for the crack k have the relationship

$$Q_k = Q_{r,k}\left(\frac{\Delta p_k}{\Delta p_{r,k}}\right)^{1/n_k} \qquad (4)$$

The total volume of air flow into the interior through the cracks is zero, that is

$$\sum Q_k = 0 \qquad (5)$$

Substituting eqn. (3) into eqn. (4), the inside pressure and the volumetric air flow through each crack are found iteratively by use of eqn. (5).

3.2. Model house and conditions for calculation

The model house used for calculations is a single room with dimensions 12.5 m wide, 8 m deep and 2.4 m high. The wind pressure coefficients are shown in Table 5. In case 1, the environmental condition is such that there are no obstacles around the house. In case 2, the houses are constructed close to one another.

The indoor temperature is a constant 20 ℃. The outdoor temperature varies from −10 ℃ to 20 ℃ and the wind speed varies from 0 to 8 m/s.

TABLE 5

Wind pressure coefficient for calculation

Environmental condition	Case 1	Case 2
Walls		
East	0.6	0.06
South	0.6	0.06
West	−0.4	−0.04
North	−0.4	−0.04
Attic	−0.3	−0.03
Crawl space	0.1	0.01

3.3. Calculated results

The calculated results are shown graphically in Fig. 9. For example, when the wind speed is 4 m/s and the outdoor temperature is 0 ℃, the air infiltration rate for the house with an airtightness of rank 4 is 1.1 ach for the environmental condition in case 1, and 0.45 ach in case 2. For the house with an airtightness of rank 2, the air infiltration rate

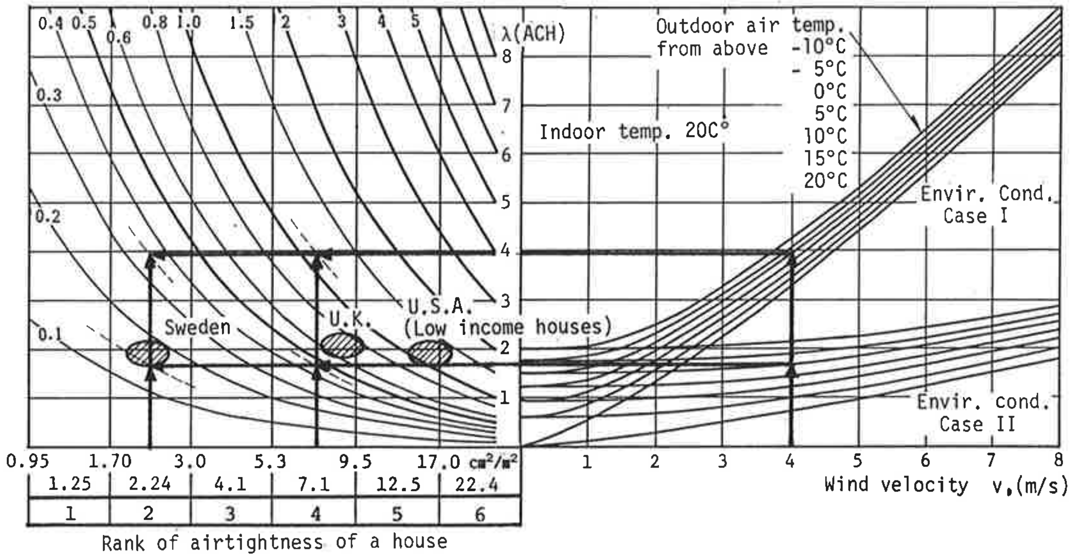

Fig. 9. Relationship between airtightness and air infiltration.

is as low as 0.35 ach for case 1 and 0.15 ach for case 2.

Using Fig. 9, the air infiltration rate can be easily determined, corresponding to the airtightness rank.

3.4. Discussion

In Section 2, the houses with high CO_2 and NO_2 concentrations had an airtightness rank of 3. According to Fig. 9, the air infiltration rate in the houses with an airtightness rank of 3, is about 0.3 ach under the environmental condition of case 2 (each measured house was situated in a densely occupied housing estate) and an outside air temperature of 0 °C. Such airtight houses should be mechanically ventilated to maintain clean indoor air.

Figure 9 includes the mean ranges of air infiltration for the following three examples.

(1) Grot and Clark [13] measured air infiltration in 266 units of low income houses with one or two stories in the United States. The measuring method used was the concentration decay technique using SF_6. Measurements were made from January to June, 1979, considering various outdoor conditions. The mean air infiltration rate was 1.22 ach. The peak air infiltration rate was between 0.5 and 0.75 ach, with the distribution from 0 to 4.31 ach. The airtightness of those houses was measured and the results are shown in Fig. 2. The mean value for the A_r^* was 15.6 cm^2/m^2 in rank 5.

(2) Warren and Webb [14] measured air infiltration 130 times in twenty-five different types of unoccupied houses with less than three stories using the N_2O concentration decay technique. The mean value of air infiltration rate was 0.7 ach. Ten percent of all measured houses had values greater than 1.3 ach. The airtightness is around rank 4, as shown in Fig. 2.

(3) Kronvall's measurements [15] in twenty-four various types of Swedish houses reveal a small mean value of air infiltration of 0.16 ach. Those houses have an mean airtightness of rank 2. For one of twenty-five houses shown in Fig. 2, air infiltration was not measured.

The mean ranges of air infiltration for the three cases in different countries are laterally aligned in the chart of Fig. 9. This is interesting, because the effect of the wind force and the indoor–outdoor temperature difference on the pressure difference across the building envelope is nearly equal in these three cases.

4. HEATING AND VENTILATING SYSTEMS AND TYPES OF COOKING APPLIANCE CORRESPONDING TO THE RANK OF AIRTIGHTNESS

In order to minimize air infiltration, maintain clean indoor air and avoid an extreme decrease in internal pressure, the optimum combination of heating and ventilat-

TABLE 6

Heating* and ventilating systems and cooker types corresponding to the airtightness rank of a house

Rank	1	2	3	4	5
Specific leakage area, A_r	1.25 Remarkably airtight	2.24 Airtight	4.1 Slightly airtight	7.1 Slightly leaky	12.5 Leaky
Heating system	Central system and passive solar heating	Central system (living and bedrooms are heated)	Local heaters (vented heater or heat pump)	Movable local heaters (vented or semi-vented heater and electric heater "Kotatsu")	Movable local heaters (unvented heater and electric heater "Kotatsu")
Cooker type	Electric	Electric	Gas	Gas	Gas
Ventilation system					
Living and bedrooms	Central mechanical ventilating system with heat exchanger	Mechanical ventilation with heat exchanger	Mechanical ventilation only for living room	Natural ventilation by air inlet	Natural ventilation by opening windows
Kitchen		Local mechanical ventilation with heat exchanger	Local mechanical ventilation	Mechanical ventilation	Mechanical ventilation
Bathroom and toilet		Mechanical ventilation	Mechanical ventilation	Natural ventilation by air inlet	Natural ventilation by opening windows

*A vented heater takes outside air for combustion and expels the exhaust outdoors. A semi-vented heater takes indoor air for combustion and expels the exhaust outdoors. A "Kotatsu" is a traditional Japanese electric heater which is mounted under a low table.

ing systems and types of cooking appliance should be designed to correspond to a house's airtightness rank.

Table 6 shows examples of the combination of systems corresponding to airtightness rank. The type of heating system which does not allow exhaust to enter into the room is suggested for houses in ranks 1 - 4. Electric cooking appliances are suggested for houses in ranks 1 and 2. Corresponding to these systems, the living room, bedrooms, bathroom and toilet should be designed for mechanical ventilation in houses in ranks 1 - 3, considering the results described in Sections 2 and 3. The mechanical ventilation system including an air-to-air heat exchanger is suggested for houses in ranks 1 and 2. As the house in rank 1 is almost airtight, passive solar heating and a central ventilating system, including a heat exchanger, are suggested.

In Japan, a large capacity fan with an air flow rate of more than 400 m^3/h for the static pressure of 100 Pa is often used to exhaust smoke generated by cooking in the kitchen of newly constructed houses. When such a large capacity fan is operated in an airtight house, the internal pressure decreases significantly.

Murakami and Yoshino [9] reported that the internal pressure of an airtight apartment, with a floor area of 67 m^2, in rank 2, with such a large capacity fan was −120 Pa below the external pressure for the extracted flow rate of 360 m^3/h. When the fans for the toilet and the bathroom were operating at the same time, the air in the toilet and the bathroom was sucked back into the kitchen by way of the entrance hall, due to the high pressure difference across internal doors. When the doors and windows were opened under such conditions, they had to be pulled with undue force. The doors also closed forcefully, making the possibility of catching one's finger in the suddenly shutting door all too likely. Therefore, it is necessary to install an air inlet with a large area (Murakami and Yoshino recommended that the diameter of the air inlet should be 15 cm) in order to avoid the excessive decrease of internal pressure, or to install a fan for intake of outside air.

5. CONCLUSIONS

The relationship between airtightness and indoor air quality was shown, on the basis of measurements taken in thirteen detached wooden houses. Such houses have an effective leakage area per floor area, A_r^*, of 3.77 - 16.1 cm^2/m^2. The houses plotted in airtightness rank 3 with A_r^* from 3.0 to 5.3 cm^2/m^2 are comparatively airtight among Japanese detached houses. The concentration of CO_2 in the living rooms of the two houses with unvented portable oil heaters was very high. A daily mean value of CO_2 concentration was 4990 ppm for one house and 2240 ppm for the other house. Aside from these two houses, the daily mean value of CO_2 concentration in five out of seven houses with A_r^* of rank 3 was 1200 to 2000 ppm. The correlation coefficient between CO_2 and NO_2 in each house was 0.90.

The chart for predicting air infiltration for a single-room flat from airtightness rank was given assuming a uniform distribution of cracks over the building envelope. The air infiltration rate, in houses with airtightness rank 3, was estimated to be about 0.3 ach under the conditions of an outside–inside temperature difference of 20 °C and wind speed of 4 m/s.

Finally, considering the measurements of airtightness and indoor air quality, and the discussion of predicting airtightness and air infiltration, optimum combinations of heating and ventilating systems and types of cooking appliances were suggested to correspond to the airtightness rank of a house.

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APPENDIX

In the case of an orifice plate, the relationship between the pressure difference across an orifice plate and the volumetric air flow is

$$\Delta p = \frac{\rho_o}{2}\left(\frac{Q}{A} \times \frac{10000}{3600}\right)^2$$

$$= \frac{\rho_o}{2}\left(\frac{2.78Q}{A}\right)^2 \qquad \text{(A1)}$$

where Q is the volumetric air flow (m^3/h) and A is the effective orifice area (cm^2).

Therefore, the effective orifice area is obtained by

$$A = 2.78Q\left(\frac{2}{\rho_o}\,\Delta p\right)^{-0.5} \qquad \text{(A2)}$$

Substituting eqn. (1) into eqn. (A2), the effective orifice area (effective leakage area) is given by

$$A = 2.78Q_r\left(\frac{\Delta p}{\Delta p_r}\right)^{1/n}\left(\frac{2}{\rho_o}\,\Delta p\right)^{-0.5} \qquad \text{(A3)}$$

If $\Delta p = \Delta p_r$, eqn. (A3) is rewritten simply as

$$A_r = 2.78Q_r\left(\frac{2}{\rho_o}\,\Delta p_r\right)^{-0.5} \qquad \text{(2)}$$

The value of Q_r depends on the value of Δp_r. Therefore, it is significant how the value of Δp_r is selected. Tamura [16], Hildon [17] and Sherman and Grimsrud [18] gave Δp_r the values of 74.7 Pa (0.3 inches H_2O), 50 Pa, and 4 Pa, respectively. In Japan, Δp_r is usually given the value of 9.8 Pa (= 1 mm H_2O). Considering the pressure range exerted upon the building surface in a natural environment and the ease of measuring with the fan pressurization technique, it is reasonable to select 9.8 Pa (= 1 mm H_2O) as the reference pressure difference.