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INVESTIGATION OF INDOOR THERMAL ENVIRONMENT, AIR QUALITY, AND ENERGY CONSUMPTION IN NEW DETACHED HOUSES OF WOOD-FRAME CONSTRUCTION IN A SMALL CITY IN JAPAN

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The authors investigated indoor thermal environment, airtightness, indoor air quality, and energy consumption in thirteen new houses of wood-frame construction in a local city of Japan in the winter of 1985. All houses had thermally-insulated walls, ceilings, and floors, except for one house which had a concrete floor without insulation under the floor. Eight houses had concrete floors on the first level of the structure. Seven houses out of eight had hot-water pipes embedded in the concrete for floor heating and thermal insulation under the floor on the grade. Three houses out of seven also had fan coil units in the bedrooms on the second floor. The six other houses without floor heating had oil or gas local space heaters. The authors found differences in temperature profiles between the houses with floor heating and those with space heaters. The effective leakage area per floor area obtained by the fan pressurization method was distributed from 3.8 to 16 cm^2/m^2. The concentration measurements of CO_2 and NO_2 in the living rooms showed that the two houses with unvented oil space heaters were more polluted than the other houses. The total annual amount of energy consumption was distributed from 46 to 100 GJ.

INTRODUCTION

In Hokkaido, the northern-most island of the Japanese Archipelago, the newly constructed residential buildings are well insulated and well heated due to the severe climate in the winter and to the significant concern for improvement of the indoor thermal environment since the end of the World War II. The Hokkaido local government originally passed legislation concerning the insulation of houses. This law has been revised several times. Nowadays, newly constructed houses have heavy insulation in many cases, that is, the depth of fiberglass insulation in the ceiling, walls, and floor is 20 cm, 15 cm, and 10 cm, respectively.

On the other hand, the Japanese national government passed legislation concerning building insulation standards for the first time after the oil crisis in 1973. This law prescribed a recommendation for the insulation performance of a housing envelope in each region of Japan. As a result, the mean ratio of newly constructed houses with a partially or totally insulated envelope in 1985 was 88% in all of Japan according to the survey of the Glass Wool (Fiberglass) Association of Japan. Also, in Sendai, a local city in the Tohoku region, newly constructed detached houses have become more and more airtight and highly insulated. In such houses, it is expected that the quality of the indoor thermal environment will be better than that of existing houses. But there is the possibility of indoor air pollution, because unvented oil or gas space heaters are still popular in many homes.

The authors have investigated indoor temperature, airtightness, indoor air quality, and energy consumption in 13 units of new, detached houses in Sendai. There are many existing reports which reveal indoor temperature or indoor air quality in Japan. For example, Hasegawa and Yoshino (1987) showed the results of indoor temperature measurements of 139 houses in the Tohoku region and compared them with other measurement studies. And Nakai et al. (1987) reported the results of NO_2 concentration measurements in all-electric houses and houses using gas to prepare meals. However, there are no reports which investigate many factors relating to indoor climate and energy consumption in houses.

Sendai is the main city of the Tohoku region, which is in the northern portion of Honshu Island, and is located near the coast of the Pacific Ocean. The latitude of Sendai is 38°16'. The mean outdoor temperature in January is 0.9°C.

DESCRIPTION OF HOUSES MEASURED AND MEASUREMENT PERIOD

Table 1 describes the houses measured. All houses were built by the wood-frame construction method. The floor area of the houses measures from 105 to 183 m^2, which was nearly equal to or larger than the average of detached wooden houses throughout Japan [105 m^2 in 1983, as given by the Bureau of Statistics, Office of the Prime Minister, (1984)]. The occupants are the middle classes. Figure 1 illustrates the floor plans of the first floors of the houses in this study. These houses were constructed between 1981 and 1984. All of the structures have thermally insulated walls, ceilings, and floors, except for house no. 6 which has a concrete floor without insulation under it. The insulation material used was fiberglass. The depth of insulation in house no. 7, for example, which is the most heavily insulated, is 15 cm for the walls and ceiling, and 5 cm for the floor. The windows of all houses had double glazing or double sashes.

The houses constructed by contractor "A" had oil or gas space heaters for heating at least the living room. The oil or gas space heaters were divided into two types; one was an unvented heater and the other was a vented heater. An unvented heater takes in room air for combustion and expels the exhaust into the room. A vented heater takes in outside air for combustion and expels the exhaust outdoors. House no. 2 had an unvented oil space heater, which supplied hot air by a fan, for the living/dining room. House no. 4 had a vented oil heater for the living room as well as an unvented portable oil heater for the dining room. The other houses had vented oil heaters for the living room or the living/dining room. The main bedrooms measured had no space heater. The houses constructed by contractors "B" and "C" had concrete floors, including hot water pipes for floor heating and thermal insulation between the floor and the ground. The exception was house no. 6, which had a concrete floor without floor heating, but had a vented oil heater for the living and dining rooms. The three houses out of seven with floor heating also had fan coil units in the bedrooms of the second floor. In six houses out of thirteen with a space heater or floor heating, an electric heater "Kotatsu" is also used in the living room. A "Kotatsu" is a Japanese style electric heater which is mounted under a low table covered with a quilt. People sitting on the floor heat their legs under the low table.

The investigated structures without floor heating were typical among the newly-built houses in Sendai, but the houses with floor heating are not so popular and are built by only two or three contractors. The measurements were made during January and February of 1985.

INDOOR THERMAL ENVIRONMENT

Method of measurement

Temperatures at six points in each house were measured continuously for seven to ten days by resistance thermometers. The number of days for measurement was different between the houses because of the need to accommodate the occupants. The points measured, which are shown in Fig. 1, were in the living room (5 cm and 1.1 m above the floor level), the main bedroom, the entrance hall, outside the house, etc. Radiant temperature was measured by using a globe thermometer in the living room at a point 1.1 m above the floor level.

Outdoor temperature during the measurement period

The average outdoor temperature was about -0.6°C for the first half of the measurement period (Jan. 25 to Feb. 3) and about 2.3°C for the latter half of that period (Feb. 5 to 12).

Table 1. Description of measured houses.

House number	Date of completion	Floor area (m^2)	Depth of insulation (cm)† Wall	Floor	Ceiling	Window	Heating in living room Equipment	Hours* in a day	Months in a year
1	Jan.1983	109	5	5	7.5	D.S.	Vented oil heater	9.8	--
2	Jan.1983	105	5	5	7.5	D.S.	Unvented oil heater & "Kotatsu"	8.9	4.6
3	Jan.1983	109	5	5	7.5	D.S.	Vented gas heater	6.5	4.6
4	Mar.1983	110	5	5	7.5	D.S.	Unvented & vented oil heaters	8.9	4.3
5	Dec.1984	109F	10	2.5	10	D.S.	Floor heating & "Kotatsu"	2.0 morning 1.5 evening	--
6	Sept.1984	142F	10	-	10	D.S.	Vented oil heater & "Kotatsu"	9.9	4.3
7	Sept.1984	183F	15	5	15	D.S.	Floor heating	2.0 morning	2.0
8	Jan.1982	110	5	5	7.5	D.G.	Vented oil heater & "Kotatsu"	10.2	4.3
9	Oct.1984	152F	5	5	10	D.S.	Floor heating	2.0 morning 2.0 evening	--
10	Mar.1983	147F	5	5	10	D.G.	Floor heating & "Kotatsu"	1.0 morning 2.5 evening	6.6
11	Aug.1983	163F	5	5	10	D.S.	Floor heating	2.5 morning 3.0 evening	4.0
12	June1981	120F	5	5	10	D.G.	Floor heating	2.0 morning 2.0 evening	3.6
13	Aug.1981	109F	5	5	10	D.G.	Floor heating & "Kotatsu"	0.5 morning 1.0 evening	4.0

House number	Ventilation in living room	Heating equipment in bedroom	Family size	The age Max	Min	House builder
1	Natural	none	4	37	7	A
2	Natural	none	3	34	5	A
3	Natural	none	5	46	11	A
4	Natural	none	5	44	8	A
5	Mechanical‡	Electric heater	3	37	8	B
7	Mechanical	none	4	42	12	B
8	Natural	none	4	35	0	A
9	Mechanical	Fan coil unit & "Kotatsu"	6	72	3	C
10	Natural	"Kotatsu"	4	44	12	C
11	Natural	Fan coil unit	5	45	9	C
12	Mechanical	Fan coil unit	4	35	3	C
13	Mechanical	Floor heating	4	47	13	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. "Kotatsu" is a Japanese style electric heater which is mounted under the low table covered with a quilt.
*The average in winter for the floor heating and during the measuring period for the others
†Insulation materials are glass wools.
‡"Mechanical ventilation" means an exhaust fan unit, which is situated in outer wall, with air-to-air heat exchanger, except for house #13.

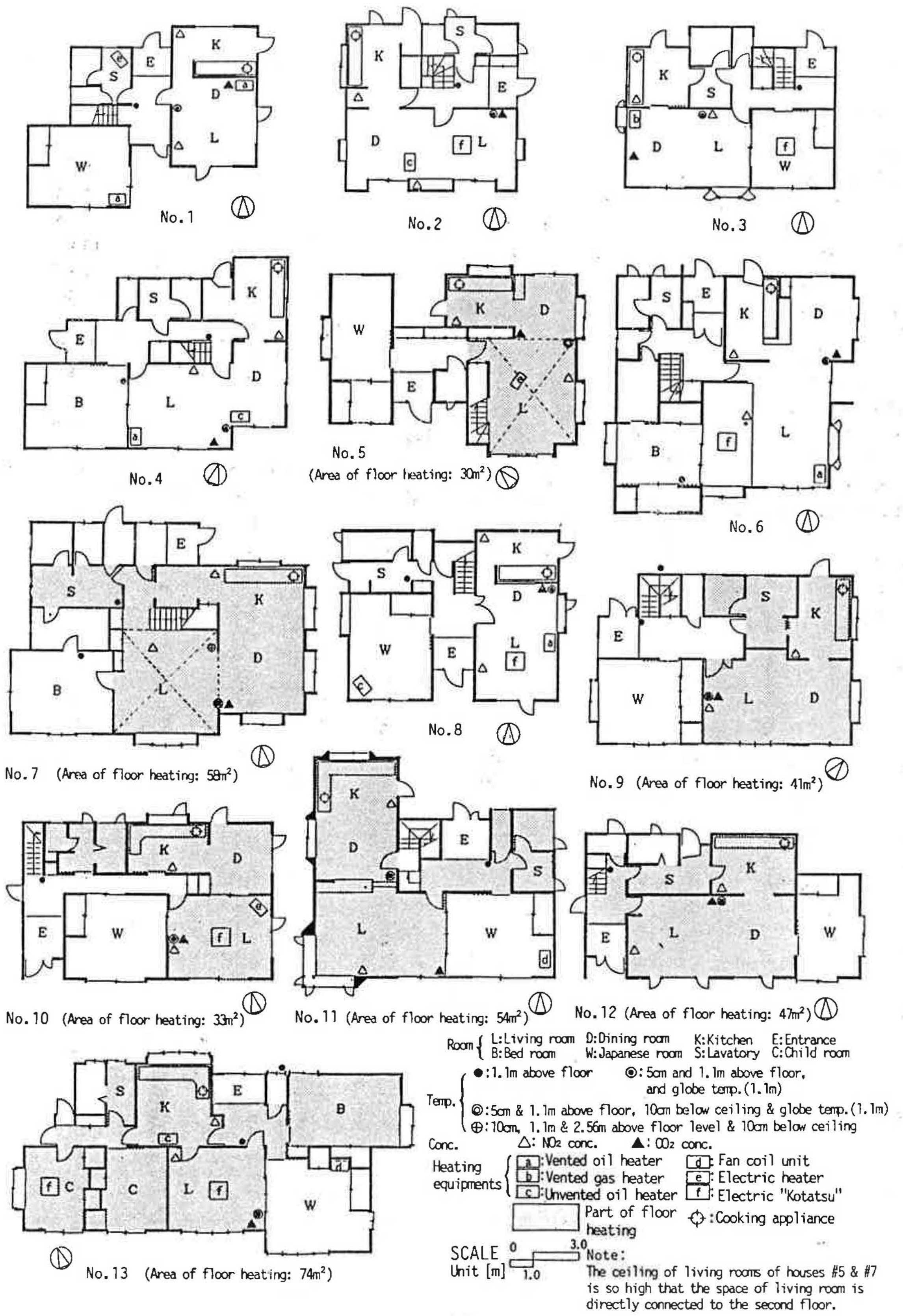

Fig. 1. Floor plans of the first floor of the houses measured.

Profiles of room temperatures

Figure 2 shows the average room temperature profiles of house no. 1 with a vented oil heater installed in the living room and of house no. 7 furnished with floor heating. The room temperatures, read every 30 minutes, were averaged for the measurement period. The living room temperature at a point 1.1 m above the floor level in house no. 1 was maintained around 20°C during the evening family time after supper. But after the heater was turned off, the room temperature fell rapidly and became 10°C by daybreak. The living room temperature at a point 5 cm above the floor level was 6°C lower than the temperature at 1.1 m. There was a high temperature stratification in the living room. Radiant temperature in the living room was 1°C lower at the maximum than the dry-bulb temperature during the heating time. The temperatures of the entrance hall and the main bedroom were lower and remained between 5 and 10°. The high temperature stratification in the living room seemed to be due to cold air infiltration from the unheated corridor or the entrance hall. On the other hand, the room temperatures of house no. 7 with floor heating remained high all day long. Although hot water was circulated through pipes in the concrete floor for only two hours from 7 to 9 AM, living room temperature at a point 1.1 m high was 17 - 22°C all day long due to the heat storage effect of the concrete floor. There was no temperature difference between the points 1.1 m and 5 cm above the floor level in the living room. Radiant temperature was nearly equal to or a little higher than the dry-bulb temperature. The temperature of the bedroom and that of the washroom was 15 - 20°C.

Figure 3 shows the temperature profiles of the living rooms of the other houses with space heaters or floor heating, respectively. Each group of living rooms had different temperature profiles from one another, as shown in Fig. 2. Although the operating hours of floor heating were short, for example only 5.5 hours at the maximum among the houses with floor heating, the temperature of each living room remained stable all day long. The outdoor temperatures were measured outside of several houses during two different periods. Therefore, three and five temperature profiles are shown in Fig. 3a and 3b.

Relationship between outdoor and room temperatures

Figure 4 shows the regression lines between the daily mean outdoor temperature and the indoor temperature in three different spaces; living room, main bedroom, and entrance hall. In the living room, two different regression lines are shown for each house. The broken line represents the temperature averaged during the evening family time. The other represents the temperature averaged during a whole day. It is generally expected that the slope of the regression line comes near to zero when a space is well heated. In almost all of the houses, the slope is up toward the right, that is, the indoor temperature increased during the day with higher outdoor mean temperature. But

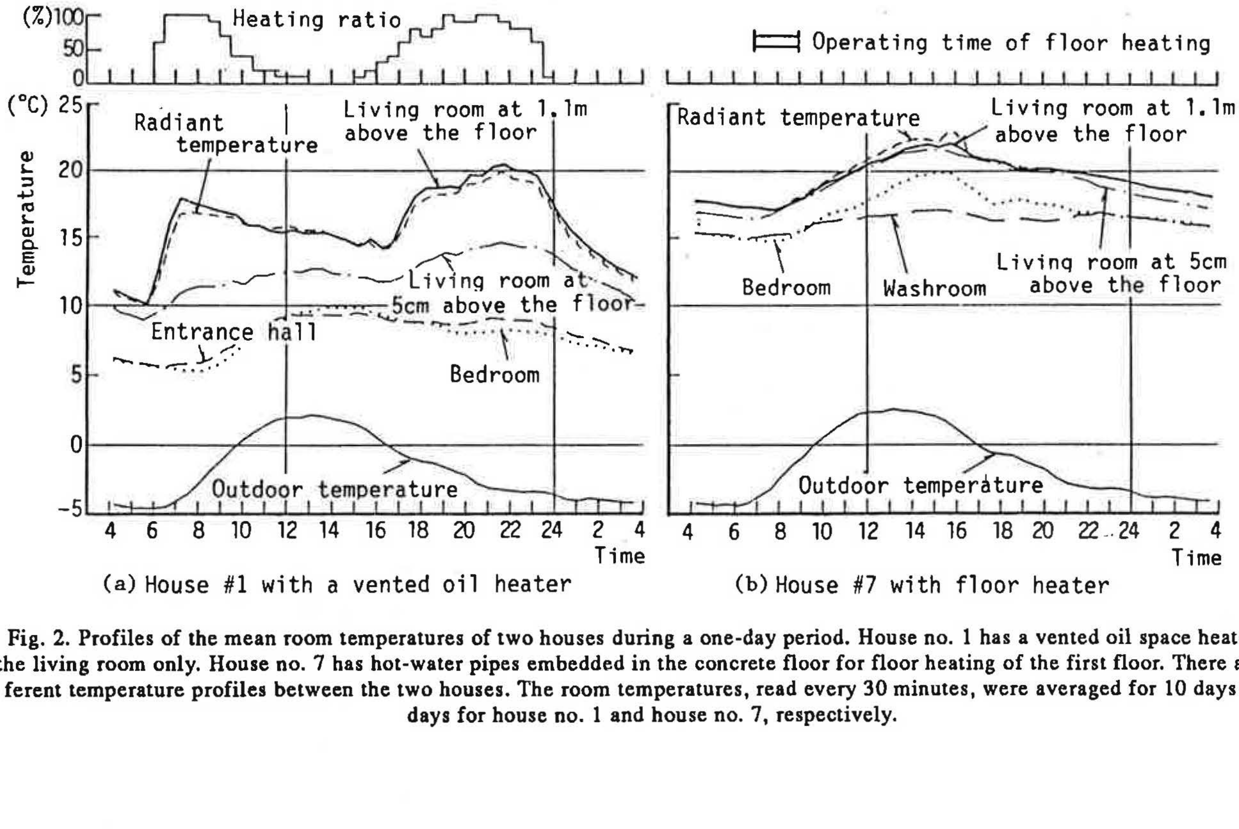

Fig. 2. Profiles of the mean room temperatures of two houses during a one-day period. House no. 1 has a vented oil space heater for the living room only. House no. 7 has hot-water pipes embedded in the concrete floor for floor heating of the first floor. There are different temperature profiles between the two houses. The room temperatures, read every 30 minutes, were averaged for 10 days and 7 days for house no. 1 and house no. 7, respectively.

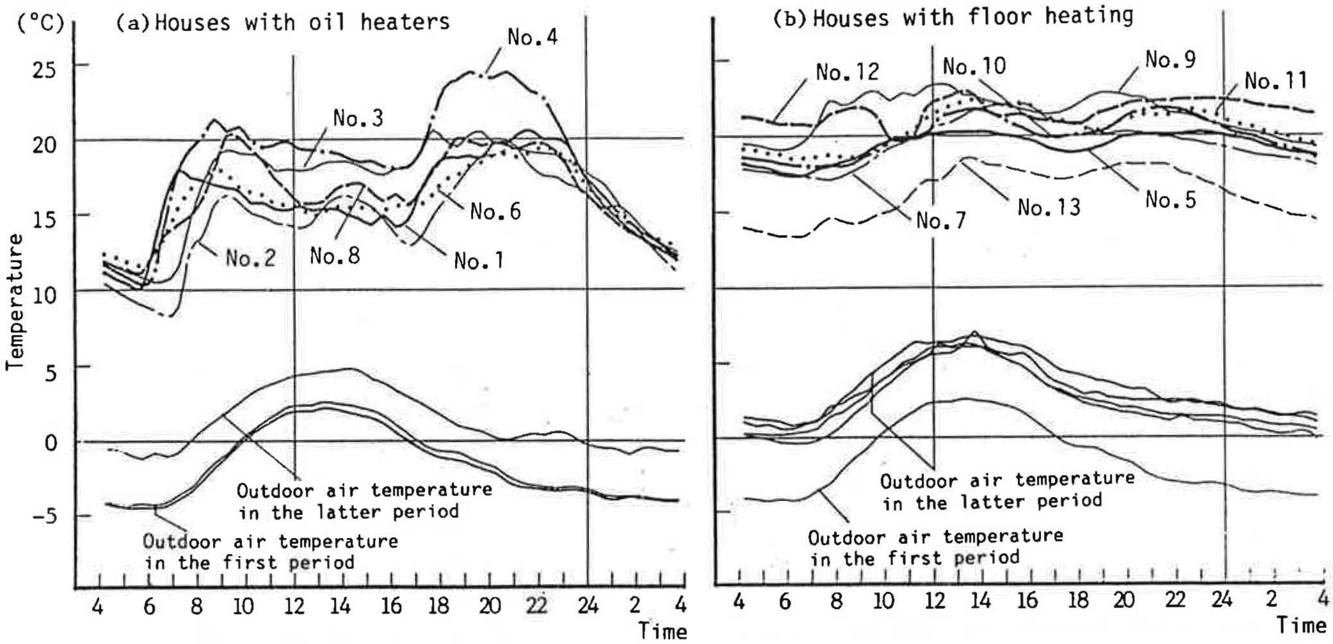

Fig. 3. Profiles of the mean living room temperatures at the point 1.1 m in height in the houses with a space heater or floor heating. Each group of living rooms has different temperature profiles from one another, as shown in Fig. 2. The outdoor temperatures were measured outside of several of the houses during two different periods. Therefore, 3 and 5 profiles were shown in Fig. 3a and 3b.

in the living rooms of three of the houses, the indoor temperature averaged during the evening family time decreased during the day with higher outdoor mean temperature. The slope of the regression line is relatively sharp in main bedrooms and entrance halls. The correlation coefficient of each space is greater in the order of the living room, bedroom, and entrance hall. Therefore, it can be said that the indoor temperature of the bedroom and the entrance hall greatly depends upon the outdoor temperature.

When the outdoor temperature was 0°C, the mean temperature of the houses with a space heater was 21.9°C during the evening family time in the living room, and 16.5°, 11.3°C, and 8.6°C (daily mean value) in the living room, main bedroom, and entrance hall, respectively. On the other hand, the mean temperature of the houses with floor heating for an outdoor temperature of 0°C was 21.9°C during the evening family time in the living room. That temperature is the same as the value of the living room with a space heater. The daily mean value in the living room, main bedroom, and entrance hall was 19.0°C, 14.2°C, and 12.6°C, respectively. These temperatures were higher than those of the houses with a space heater.

According to the measurement results by Hasegawa et al. (1980) in houses with a space heater, which were constructed by the local public housing corporation of Miyagi Prefecture, the mean temperature for an outdoor temperature of 0°C was 22.0°C in the evening family time in the living room, and 15.1°C, 8.0°C, and 6.2°C (daily mean value) in the living room, main bedroom, and corridor, respectively. The living room temperature during the evening family time measured in 1980 was nearly equal to the living room temperature with a space heater as measured during the present study. But the daily mean temperature of each room was 4°C to 6°C lower than that of the present study.

Vertical temperature difference in living room

Figure 5 shows the relationship between the vertical temperature difference and the indoor-outdoor temperature difference. The vertical temperature difference means the temperature difference between 5 cm and 1.1 m above the floor level. These temperatures were averaged during the evening family time or during the whole day for the measurement period. The points plotted were divided into two groups, space heaters and floor heating. The vertical temperature difference measured in houses with a space heater was lower. The ratio of the temperature difference between 5 cm and 1.1 m in height to the indoor-outdoor temperature difference (non-dimensional vertical temperature) is 0.2 to 0.3. According to the results of indoor temperature measurement of 139 houses in the Tohoku region by Hasegawa and Yoshino (1987), the non-dimensional vertical temperature of existing houses with space heaters was distributed from 0.2 to 0.6. That value of 0.2 to 0.3 in this measurement is comparatively low.

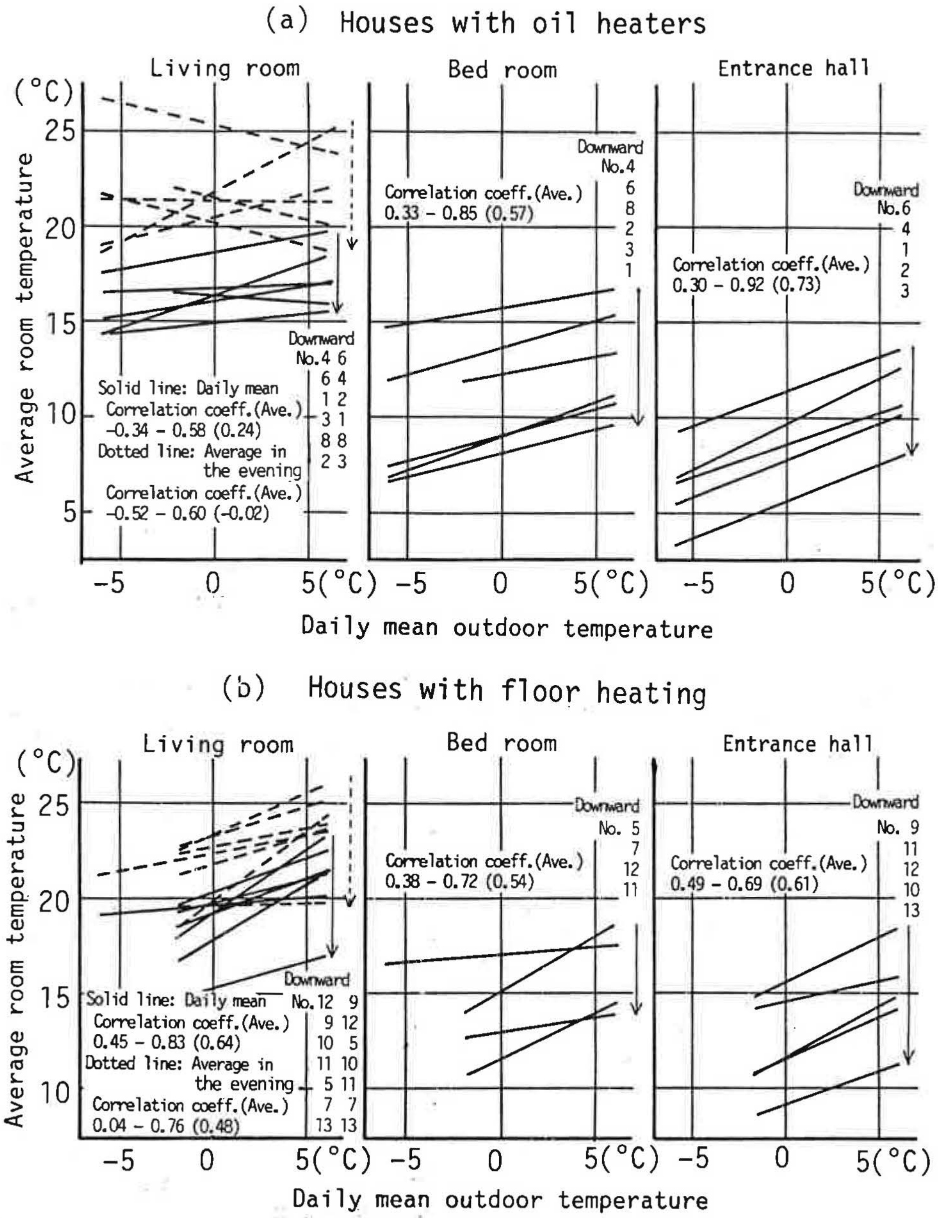

Fig. 4. Regression lines between the daily mean outdoor temperature and the indoor temperature in three different spaces; living room, main bedroom, and entrance hall. In the living room, two different regression lines are shown for each house. The broken line represents the temperature averaged during the evening family time. The solid line represents the temperature averaged during a whole day.

On the other hand, the vertical temperature difference of the houses with floor heating was very small. The nondimensional vertical temperature was less than 0.1. In some cases, however, the temperature at 5 cm above the floor level was higher than the temperature at 1.1 m. In houses no. 5 and no. 7, the temperature at 10 cm below the ceiling was measured in the living rooms which had a high ceiling just below the two-story roof. In house no. 5, the room temperatures during the evening at points 5 cm and 1.1 m above the floor and 10 cm below the ceiling were 21.2°C, 21.8°C, and 21.9°C, respectively. In house no. 7, the room temperatures at these same points were 22.1°C, 22.6°C, and 22.1°C, respectively. The vertical temperature difference was extremely small, due not only to the effect of floor heating but also to the high degree of thermal insulation and airtightness.

Radiant temperature

Figure 6 shows the relationships between the nondimensional vertical temperature and the radiant temperature difference, which is the difference between radiant temperature and dry-bulb temperature. These temperatures in the living rooms were averaged during the evening family time for about tendays.Thepointsplottedarealsodividedintotwo groups, as shown in Fig. 5, and there is a minus correlation between the two factors. In the living rooms with floor heating, not only was the nondimensional vertical temperature small, but the radiant temperature was also 1°C higher at the maximum than the dry-bulb temperature due to the effect of radiation from the floor surface. That is, the living room with floor heating was thermally more comfortable than the rooms with a space heater.

Temperatures of other rooms

Figure 7 shows the temperature difference between the living room and the other rooms averaged during the evening family time for the measurement period. Each temperature is indicated as the difference from the outdoor temperature. The temperatures of the other rooms were lower than the living room temperature in all of the houses. The ratio of the temperature of the other rooms to the living room temperature was widely distributed from 0.3 to 0.9. According to the results of the questionnaire on thermal sensation, almost all occupants perceived the temperatures of the living room and the kitchen as being "neutral," but half of the occupants perceived the temperatures of the bedroom and the entrance hall to be "a little cold."

List of symbols

- Q air flow through the building envelope (m^3/h)
- Qr air flow at reference conditions (m^3/h)
- Δp pressure difference across the building envelope (Pa)
- Δp_r pressure difference at a reference condition (Pa)
- n exponent of the pressure difference
- Ar effective leakage area at a reference condition (m^2)
- Ar* Ar per floor area; specific leakage area (cm^2/m^2)
- ρ density of air (kg/m^3)
- r_1 non-dimensional vertical temperature, which means the ratio of temperature difference between 5 cm and 1.1 m above a floor level to temperature difference between living room and outdoors
- r_2 room temperature decreasing rate, which means the ratio of various room temperatures to living room temperature. Each temperature is indicated as the difference from outdoor temperature

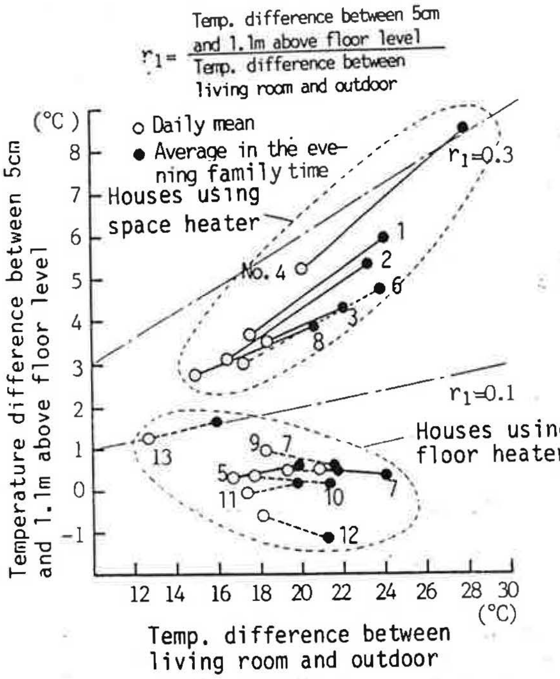

Fig. 5. Vertical temperature difference and indoor-outdoor temperature differences in the living room which were averaged during the evening family time or during a whole day for the measurement period. The points plotted are divided into two groups: space heaters and floor heating. The indoor temperature of house no. 7 was measured for two different periods.

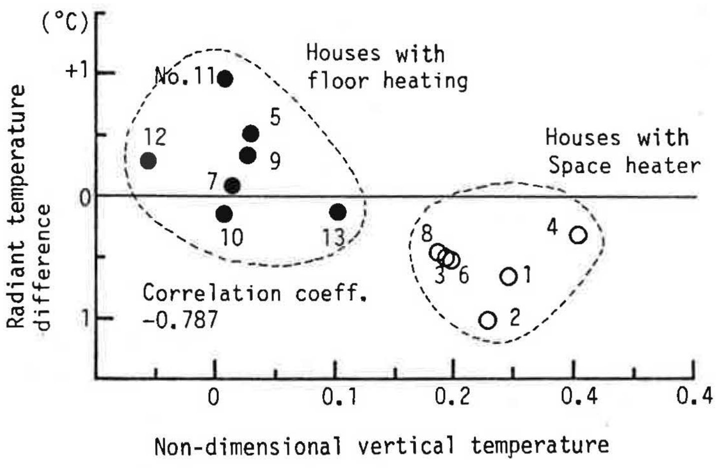

Fig. 6. The non-dimensional vertical temperature and the radiant temperature difference. The radiant temperature difference represents the difference between radiant temperature and dry-bulb temperature. These temperatures in the living rooms were averaged during the evening family time for the measurement period. The points plotted are divided into two groups as shown in Fig. 5. There is a minus correlation between the two factors.

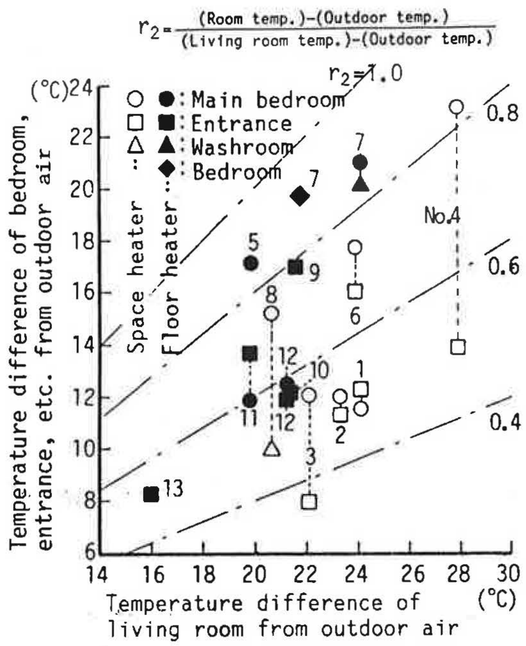

Fig. 7. Averaged temperature differences between the living room and the other rooms averaged during the evening family time for the measurement period. Each temperature is indicated as the difference from the outdoor temperature.

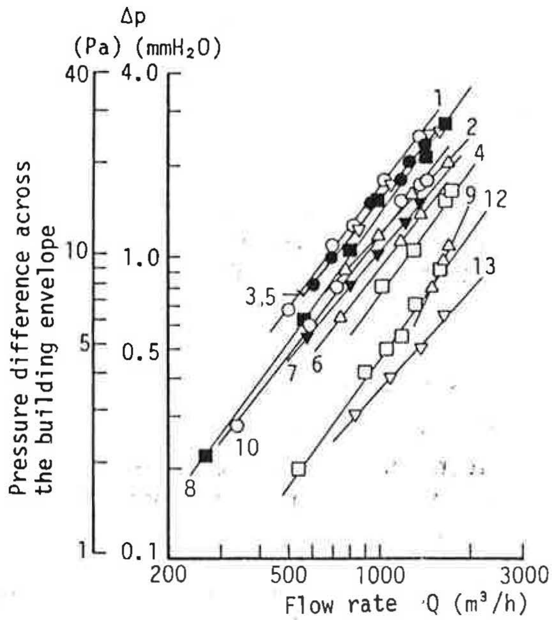

Fig. 8. Pressure difference across the building envelope and the volumetric flow rate of 12 houses, without house no. 11. The airtightness of house no. 11 could not be measured due to high wind speed despite three attempts on different days.

Table 2. Airtightness of measured houses.

House No.	Air flow Q_r(m^3/hr)	n	ELA[a] A_r(cm^2)	SLA[b] A_r^*(cm^2/m^2)
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

[a] Effective Leakage Area at 9.8 [Pa]
[b] Specific Leakage Area = ELA/floor area

AIRTIGHTNESS OF INVESTIGATED HOUSES

Method of measurement

Airtightness measurements were made by the fan pressurization method (Narasaki and Kusumi 1974; Stricker 1975). Internal pressure was increased by a fan attached to a duct penetrating a thin board set in a window. The pressure differences were measured by a capacitance manometer. Flow rate in the duct was measured by a thermistor anemometer. Measurements were carried out at the indoor-outdoor pressure difference from 2 to 30 Pa in almost all of the houses. But in leaky houses, it was impossible to increase the pressure difference more than 10 Pa.

Measured results

Figure 8 shows the relationship between the pressure difference across the building envelope and the volumetric flow rate of 12 houses, excluding house no. 11. This relationship is expressed by

$$Q = Qr\left(\frac{\Delta p}{\Delta p_r}\right)^{\frac{1}{n}} \tag{1}$$

Table 2 shows the volumetric air flow through the building envelope, Qr, for the pressure difference between the building envelope, Δp_r, of 9.8 Pa. Also shown is the exponent of the pressure difference, n of Eq. 1 estimated by regression lines. The value of exponent n for house no. 9 was unreasonably high, more than 2.0. One of the reasons may be that more than three times measurements could not be made and data obtained were unstable due to high wind speed. Except for house no. 9, the value of n ranged from 1.07 to 1.40. Table 2 also shows the effective leakage area, Ar, for each house, which can be calculated by the following equation.

$$Ar = 2.78\,Qr\,(2\Delta P_r/\rho)^{-0.5} \tag{2}$$

In Eq. 2, Δp_r is given as 9.8 Pa. The effective leakage area per floor area (specific leakage are), Ar*, is also included in Table 2. The value of Ar* was widely distributed from 3.77 to 16.1 cm^2/m^2. The airtightness of house no. 11 could not be measured due to high wind speed despite three attempts on different days.

Comparison of airtightness using effective leakage area per floor area

Figure 9 shows the effective leakage area per floor area for various houses in different countries. Where the original airtightness data were not shown as Ar for Δp_r=9.8 Pa, these data were converted, assuming 1/n=0.6. The original figure is presented in the paper by Murakami and Yoshino (1983).

The houses measured in this test were ranked 3 through 5 in airtightness. Except for houses no. 12 and no. 13, airtightness of the houses was higher than that of the houses measured in the past by Yoshino et al. (1981) in Sendai. Although there is no standard or recommendation of airtightness for a building envelope in Japan, this figure shows that the houses with rank of 3 were comparatively airtight for detached Japanese houses.

Among the houses constructed by contractor A, house no. 1, which has hinged windows with double panes, is the most airtight. Houses no. 2, no. 3, and no. 4 have sliding double sashes. House no. 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 contractor B, house no. 7, which was constructed with airtightness in mind, is the most airtight. Houses no. 5, no. 6, and no. 7 have the ventilation fan unit

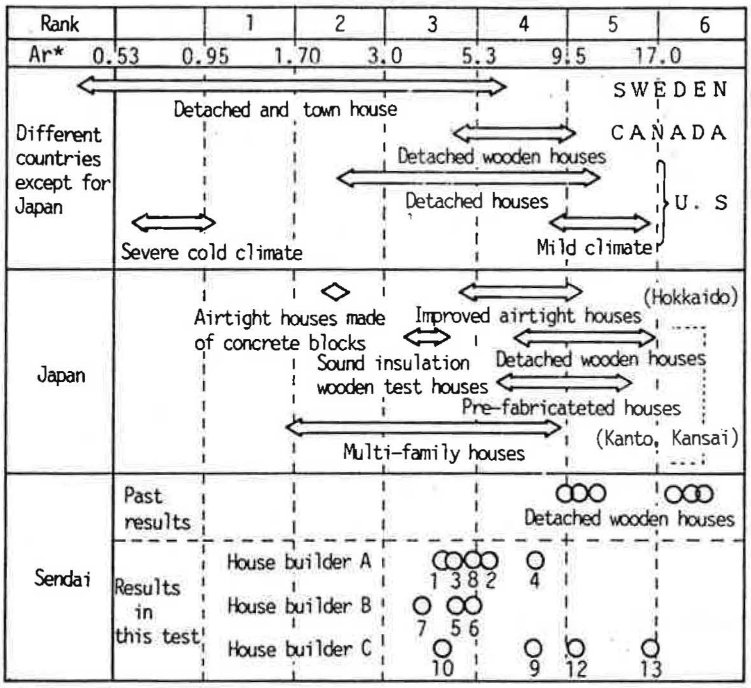

Fig. 9. Airtightness for various houses in different countries. The figures represent the specific leakage area for Δp=9.8 Pa. The original figure is presented in the paper by Murakami and Yoshino (1983).

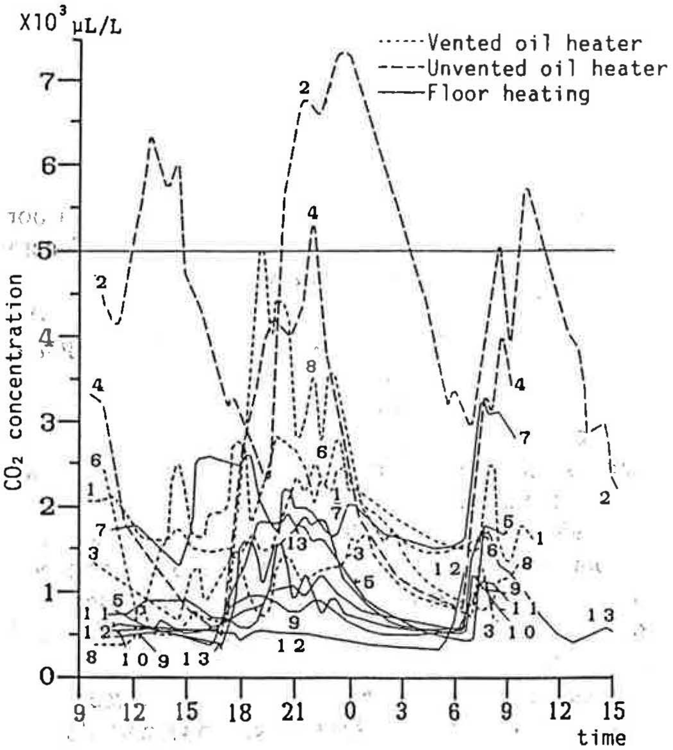

Fig. 10. Variation of CO_2 concentration measured in the living room of each house during different measuring periods. According to ASHRAE Standard 62-1981 and the other literature, it is generally felt that 5000 µL/L is an upper limit of CO_2.

with an air-to-air heat exchanger mounted in the outer wall. But the occupants in these houses stated that they felt air infiltration, even though the unit was not operating, when the outdoor wind speed was high. The airtightness of the houses constructed by contractor C varied greatly. House no. 13, which is plotted at the extreme right side, has sliding sashes and leaky sliding entrance doors. House no. 11, for which airtightness was not tested, is expected to be plotted between house no. 10 and house no. 9, considering the construction method and the type of windows and doors.

INDOOR AIR QUALITY

Method of measurement

The concentration of CO_2 was measured continuously for one or two days in the living room of each house by an infrared analyzer. The concentration of NO_2 was measured by bare detector badges exposed for three days in the living room and the kitchen. This measurement follows the method utilized by Yanagisawa and Nishimura (1980). The locations of the measurement points are shown in Fig. 1.

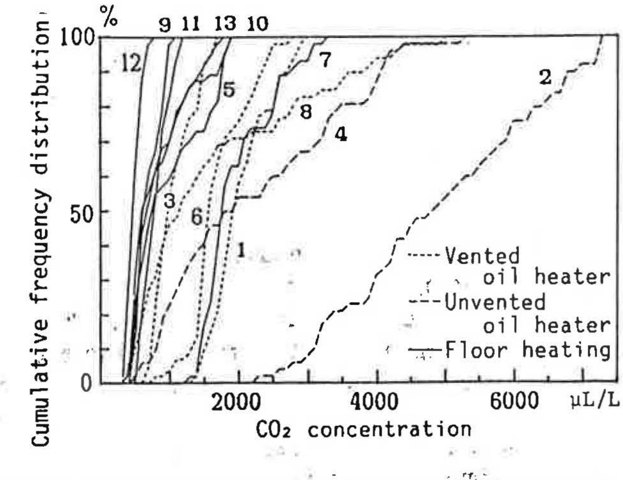

Fig. 11. Cumulative frequency distribution of CO_2 concentration.

Measured results of CO_2 concentration

Figure 10 shows the variation of CO_2 concentration measured in the living room of each house during different measuring periods. The concentration of CO_2 rose 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 9:00 PM, the concentration was distributed from 500 to 7000 µL/L. The concentration in

Table 3. Mean concentration of CO_2 and NO_2. CO_2 concentration was averaged for a day. NO_2 concentration was averaged for 2 to 3 days.

House No.	CO_2 concentration (µL/L)	NO_2 concentration (µL/L)	
		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

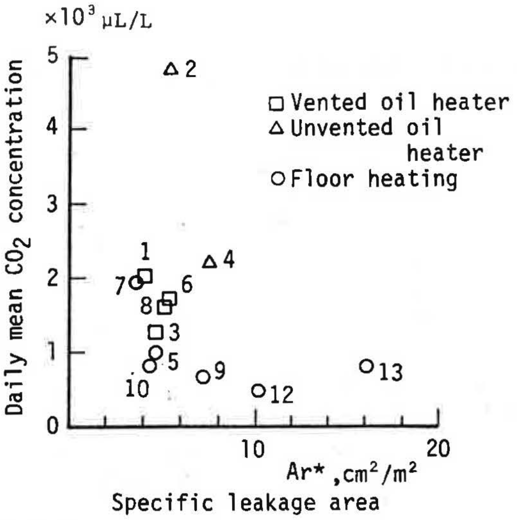

Fig. 12. Daily mean CO_2 concentration in the living room and the effective leakage area per floor area. The concentration of CO_2 is very high for the two houses with unvented portable oil heaters. With the exception of these two houses, the CO_2 concentration in five out of the seven houses with an Ar* value smaller than 6 cm^2/m^2 is more than 1000 μL/L.

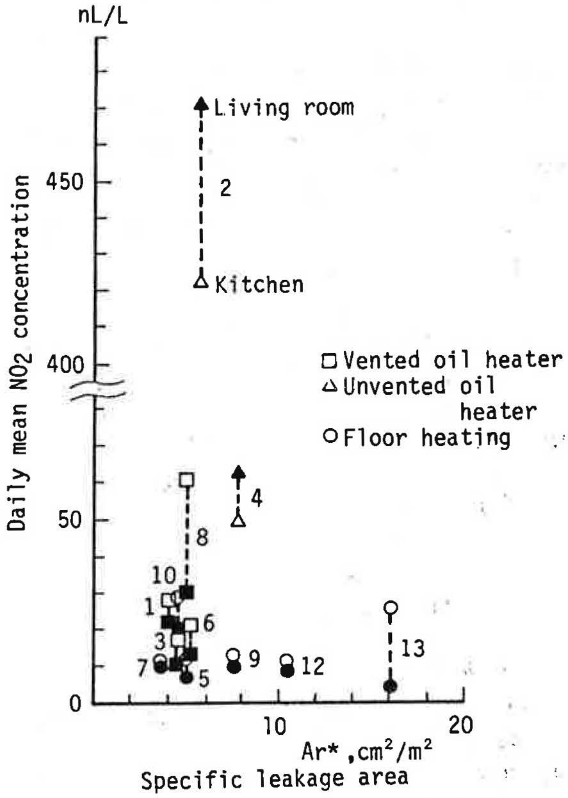

Fig. 13. Daily mean NO_2 concentration in both the living room and the kitchen and the effective leakage area per floor area. The concentration of NO_2 is extremely high in one house with an unvented portable oil heater which supplies hot air. In the houses with unvented heaters, the NO_2 concentration of the living room is higher than that of the kitchen. On the other hand, in the houses without unvented heaters, the NO_2 concentration of the kitchen was higher than that of the living room due to NO_2 generation from the gas cooking stove in the kitchen.

house no. 2 with an unvented oil heater was especially high. According to ASHRAE Standard 62-1981 and Sato (1965), it is generally felt that 5000 μL/L is an upper limit of CO_2. The Building Standards Code of Japan prescribes that the limit of CO_2 for indoor air in air-conditioned spaces of office buildings be less than 1000 μL/L.

Figure 11 shows the cumulative frequency distribution of CO_2 concentration during a day. In houses no. 1, no. 2, no. 4, no. 6, and no. 7, the CO_2 concentration was more than 1000 μL/L for more than 70% of the time. In houses no. 1, no. 2, and no. 7, the concentration was more than 1000 μL/L all day long. Unexpectedly, the concentration in house no. 2 was more than 2000 μL/L all day long. Houses no. 2 and no. 4 have unvented oil heaters. Houses no. 1 and no. 7 were the most airtight among the 13 houses measured for this test. The houses with floor heating systems, except for house no. 7, show a rather low CO_2 concentration. Table 3 shows the mean concentration of CO_2 for a one-day period.

Measured results of NO_2 concentration

Table 3 also shows the mean NO_2 concentration for two to three days in the living rooms and kitchens. The concentration in house no. 2 was extremely high. The second highest concentration was in house no. 4. In all of the houses, except for the two houses with unvented oil heaters and house no. 11, the concentration in the kitchen was higher than that of the living room due to NO_2 generation from gas cooking stoves in the kitchen.

The relationship between airtightness and indoor air quality

Fig. 12 shows the relationship between the effective leakage area per floor area, Ar*, and the daily mean concentration of CO_2. The CO_2 concentration was very high for houses no. 2 and no. 4 due to the usage of unvented portable oil heaters. With the exception of these two houses, the concentration in five out of the seven houses with an Ar* value smaller than 6 cm^2/m^2 was more than 1000 μL/L. As this sample was too small, it is difficult to say that there was a correlation between the leakage area and the CO_2 concentration. However, the figure suggests that the indoor air of the houses with an airtightness rank of less than 3 were easily polluted. Figure 13 shows the relationship between Ar* and the daily mean concentration of NO_2, which is similar to that shown in Fig. 12.

The saturation level of unvented heaters in Japan was 80% in 1986, as reported by the Research Bureau

Table 4. Measurement period of energy consumption and main energy uses.

House number	Measurement period	Main energy uses			Conversion value
		Electricity	Gas	Oil	
1	Oct.1984-Sep.1985		Cooking, hot water	Heating	Electlicity
2	Nov.1984-Oct.1985		Cooking, hot water	Heating	1kwh=3.6MJ
3	Oct.1984-Sep.1985	*	Heating, cooking and hot water	Nothing	
4	Dec.1984-Nov.1985		Cooking, hot water	Heating	City gas:
5	Mar.1985-Feb.1986		Cooking, hot water	Heating	$1m^3$=21.0MJ
6	Nov.1984-Oct.1986		Cooking, hot water	Heating	
7	Feb.1985-Jan.1986		Cooking	Heating, hot water	Propan gas:
8	Dec.1984-Nov.1985		Cooking, hot water	Heating	$1m^3$=101MJ
9	Nov.1984-Dec.1985		Cooking	Heating, hot water	
10	Oct.1984-Sep.1985		Cooking	Heating, hot water	Oil:
11	Dec.1984-Nov.1985	*	Cooking, hot water	Heating	1L=36.9MJ
12	Aug.1984-Jul.1985	*	@Cooking	Heating, hot water	
13	Oct.1984-Sep.1985		@Cooking	Heating, hot water	

All houses are using electricity for lighting, etc.
* the house with air conditioner
@ the house using propane gas, other houses using city gas

of Economic Planning Agency (1987). In traditional leaky houses with unvented heaters, it was expected that much air infiltration prevented indoor air from being polluted. But in the recently constructed houses with low infiltration and unvented heaters, there was a strong possibility of indoor air pollution.

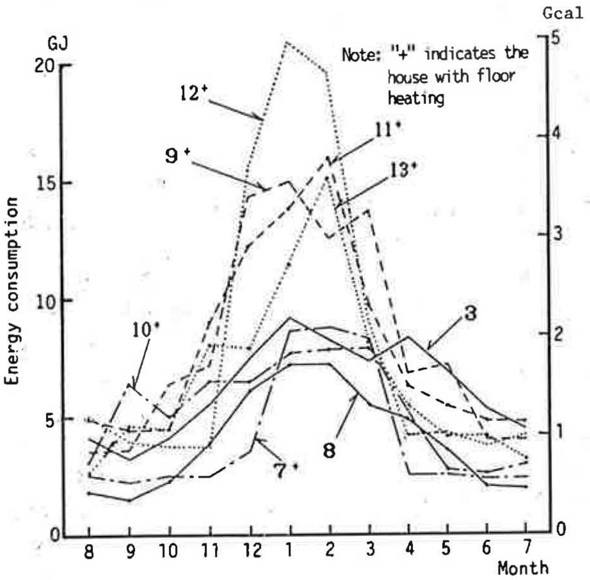

Fig. 14. Annual profiles of monthly energy consumption in 8 houses for which the energy data for 12 months was obtained. The increase in monthly energy consumption from November to March was due to space heating.

Even if an unvented heater was not used, indoor air in the many houses with an airtightness rank of less than 3 was expected to become polluted. Therefore, it is necessary to forcibly ventilate indoor air in such houses.

ENERGY CONSUMPTION

Method of measurement

Monthly consumptions of electricity, gas, and oil for each house were calculated on the basis of the utility bills of occupants. Table 4 shows the main energy uses in each house and the conversion value of electricity, gas, and oil into joule units. Data for a one-year period, which was slightly different from house to house, was obtained for the period between August 1984 and February 1986.

Annual profiles of energy consumption

Figure 14 shows the annual profiles of monthly energy consumption in eight houses for which the energy data for 12 months was obtained. The increase of monthly energy consumption from November to March was probably due to space heating. The degree of increase was high in the four houses with floor heating. The maximum value of monthly energy consumed in these four houses was more than 12.6 GJ. Three houses out of four had fan coil units on the second floor in addition to the floor heating on the first floor. The other structure, house no. 13, which

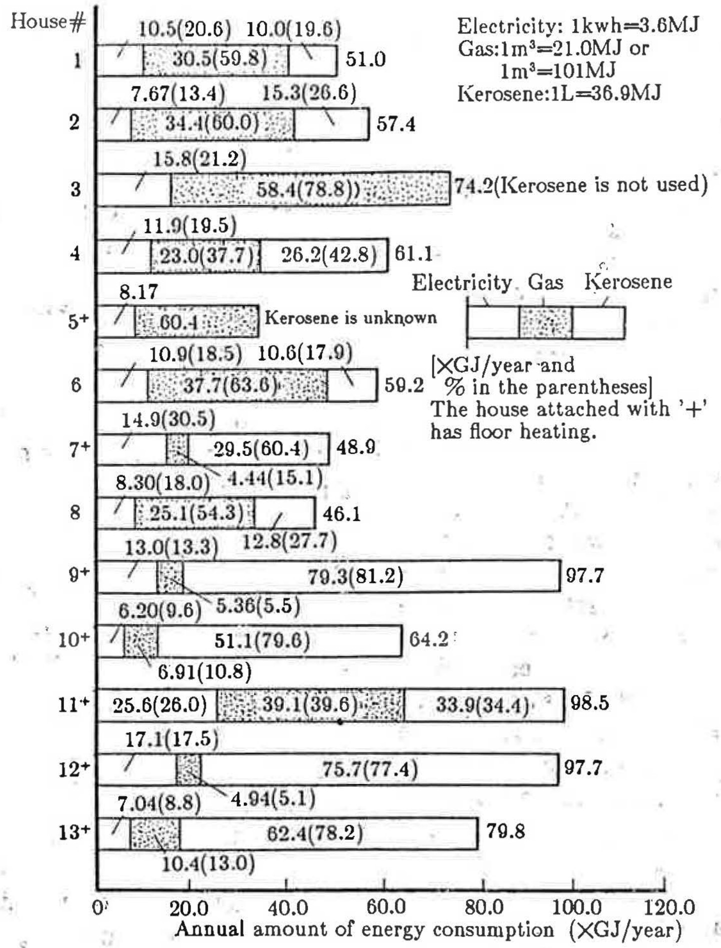

Fig. 15. Annual amount of energy consumption and its source. The amount of houses no. 9, no. 11, no. 12, and no. 13 was greater than the other houses due to a greater amount of energy consumed for space heating. But, the amount of energy consumed in well-heated house no. 7, which was the best insulated and most airtight among the investigated houses, was half that of houses no. 9, no. 11, and no. 12 and nearly equal to that of houses with a space heater installed in just the living room. These facts show that it is possible to improve indoor climate by constructing houses with good insulation and airtightness qualities, without increase of energy consumption for heating.

was a flat, had a fan coil unit in a traditional Japanese room with Tatami (woven straw) mat.

Annual amount of energy consumption

Figure 15 shows the annual amount of energy consumption and its source in each house. The amount of annual energy consumption was distributed from 46 to 100 GJ, except for house no. 5, with no data of oil consumption. The mean value was 70 GJ. The amount of energy consumed in houses no. 1, no. 2, no. 4, no. 6, and no. 8, in which the living room was only heated by an oil space heater, was rather small and distributed from 46 to 60 GJ. In house no. 4, the amount of oil consumption was greater because of usage of two oil heaters in the living room.

On the other hand, the amount of energy consumed in houses no. 7, no. 9, no. 10, no. 11, no. 12, and no. 13, all with floor heating, was distributed from 46 to 99 GJ. The amount of energy used in houses no. 9, no. 11, no. 12, and no. 13 was greater than the other houses due to the greater amount of energy consumed for space heating. That was to be expected because Fig. 14 shows the high increase during the winter due to space heating. In houses no. 9, no. 12, and no. 13, oil was used for both space heating and hot water heating. Considering the share of each kind of energy source and its end use, as shown in Table 4 in the other houses, it is estimated that more than half of the oil consumption was used for space heating.

As shown in Figs. 3, 4, and 7, of all the houses with floor heating, the living rooms were, along with the other rooms, well-heated all day long. However, the other rooms of houses with floor heating had room temperatures higher than that of the houses with space heaters. And the amount of energy consumed for heating in four houses out of seven with floor heating was greater than the other houses. But, the amount of energy consumed in well-heated house no. 7, which was the best insulated and most airtight among the investigated houses, was half that of houses no. 9, no. 11, and no. 12 and nearly equal to that of the houses with a space heater installed in just the living room. These facts show that it is possible to improve indoor climate by constructing houses with good insulation and airtightness qualities, without the increase of energy consumption for heating.

CONCLUSIONS

The authors investigated the indoor thermal environment, airtightness, indoor air quality, and energy consumption in 13 new houses of wood-frame construction in a local city of Japan in the winter of 1985. All houses had thermally-insulated walls, ceilings and floors, except for one house which had a concrete floor without insulation underneath. Eight houses had concrete floors for the first floor. The seven houses out of eight with concrete floors had hot-water pipes embedded in the concrete floors for floor heating, and had insulation under the floor on the grade. The three houses out of seven with insulation under the concrete floor also had fan coil units in the bedrooms on the second floor. The six other houses without floor heating had oil or gas local space heaters. The results measured are given as follows.

In the houses with space heaters, the living room temperature at 1.1 m above the floor was maintained around 20°C during the evening family time after supper. But after the heater was turned off, the room temperature fell rapidly and became 10°C by daybreak. In the evening family time after supper, the living room temperature at 5 cm above the floor was 4 - 8°C lower than the temperature at 1.1 m. The temperatures of the main bedroom and the entrance hall were lower than the temperature of the living room. The ratio of the temperature of the other rooms to the living room temperature was from 0.3 to 0.8. The temperature profiles of the houses were similar to those of the houses measured in 1980, which were constructed by the local public housing corporation. However, it can be said that the quality of the thermal environment of the houses recently built was better from the viewpoint of the vertical temperature difference in the living room as well as from the temperature difference between the heated living room and the other unheated rooms.

Indoor temperature in the houses with floor heating was stable during the period of one day due to the heat storage effect of concrete floors. The vertical temperature difference in the living rooms was extremely small. Radiant temperature in the living room was 1°C higher at the maximum than the dry-bulb temperature during the evening in the living room. That is, the living room with floor heating was thermally more comfortable than the rooms with a space heater.

Houses measured in this test had an effective leakage area per floor area, Ar*, of 3.77 to 16.1 cm^2/m^2. Compared with the airtightness of the other various houses, the houses which ranked 3 in airtightness with Ar* from 3.0 to 5.3 cm^2/m^2 were comparatively airtight for Japanese detached houses.

The concentrations of CO_2 and NO_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 4.99 mL/L for one house and 2.24 mL/L for the other house. The values of NO_2 were 470 nL/L and 63 nL/L, respectively. Aside from these two houses, the daily mean concentration of CO_2 in five out of the seven houses with an Ar* ranking of 3 was 1.2 to 2 mL/L.

The amount of annual energy consumption was distributed from 46 to 100 GJ, except for house no. 5 with no data of oil consumption. The mean value was 70 GJ. The amount of energy consumed in houses no. 7, no. 9, no. 10, no. 11, no. 12, and no. 13, all using floor heating, was distributed from 46 to 99 GJ. The amount of energy consumed in houses no. 9, no. 11, no. 12, and no. 13 was greater than the other houses due to a greater amount of energy consumed for space heating. But, the amount of energy consumed in well-heated house no. 7, which was the most heavily insulated and airtight among the investigated houses, was half that of houses no. 9, no. 11, and no. 12 and nearly equal to that of houses with a space heater installed in just the living room. These facts show that it is possible to improve indoor climate by constructing houses with good insulation and airtightness qualities, without an increase in energy consumption for heating.

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