AIVC 11952

Thermal Environment and Energy Performance of Well-Insulated and Airtight Houses in Tohoku District of Japan

Hiroshi Yoshino, Tohoku University, Sendai, JP
Ken-ichi Hasegawa, Shinshu University, Nagano, JP

ABSTRACT

Newly constructed residential houses in Japan are better insulated and more airtight than their predecessors to increase energy conservation. Although reduced energy consumption was expected, the energy performance of these buildings has not yet been clarified. Therefore, the indoor thermal environment and energy consumption in 300 well-insulated and airtight houses newly constructed in the Tohoku District, the northern part of Honshu Island, were investigated by a questionnaire survey. The information provided by the homeowners included the floor area, level of thermal insulation, space heating equipment, occupants behavior in regard of heating and ventilation, utility bills, problems with the indoor environment.

This paper firstly describes the characteristics of indoor thermal environment in the investigated houses and energy consumption. Secondly, the relationship between kerosene consumption for space heating and the influencing factors on energy consumption is discussed by a multi-regression analysis method. Thirdly, the influence of these factors on the heating load is estimated using computer simulations.

The energy consumption of well-insulated and airtight houses investigated consumed more kerosene than the ordinary existing houses, because of increase in heated floor area and heating hours. Computer simulation reveal that the well-insulated and airtight houses in the Tohoku District consume more energy for space heating than ordinary existing houses, in which only the living/dining room is heated. The results also show, that it would be possible to keep a comfortable indoor environment with less energy consumption than the ordinary existing houses, if the houses had an insulation comparable to R2000 houses in Canada.

Introduction

Newly constructed detached houses in Japan, especially in the northern portion of Japan, have become more and more airtight and highly insulated due to energy conservation and the demand for thermal comfort. In such houses, it is expected that the quality of the indoor thermal environment will be better than that of existing houses. However, there is the possibility of problems related to indoor air quality and humidity in the winter and the energy performance of these buildings has not yet been clarified.

The purpose of this study is to grasp the indoor thermal environment and energy performance of well-insulated and airtight houses during winter, and to obtain more information on influencing factors on the heating loads. This paper firstly describes the characteristics of indoor thermal environment in the investigated houses and the buildings' energy consumption. Secondly, the relationship between kerosene consumption for space heating and the influencing factors on energy consumption is discussed and calculation by a multi-regression analysis method are presented. Thirdly, the influence of these factors on the heating load is estimated using computer simulations. The simulation method takes the multi-zone effects of heat transfer and air flow distribution into consideration.

Characteristics of Indoor Thermal Environment

Questionnaire Survey on Indoor Environment and Occupant's Behavior

Method of Investigation. The indoor environment and energy consumption in three hundred well-insulated and airtight houses newly constructed in the Tohoku District, the northern part of Honshu Island, were investigated by a questionnaire survey in winter of 1994. These houses are equipped with mechanical ventilation system and space heating systems for the entire house. The information provided by the homeowners included the floor area, year of construction, level of thermal insulation, space heating equipment, number of occupants, occupancy schedules, occupants' behavior in regard of heating and ventilation, utility bills, problems with the indoor environment. Because it was difficult to select randomly only the well-insulated and airtight houses among detached houses in Tohoku District, the questionnaire was distributed to owners of homes constructed by the forty-five builders dealing with the well-insulated and airtight houses. The investigated region and the number of respondents are shown in Table 1. The total number of respondents is 303.

Results. Figure 1 shows the results of questionnaire survey for winter indoor environment.
Features of the houses: Floor area is in the range of 100~220m^2. There are many houses larger than 200 m^2 in Yamagata prefecture. The average floor area is around 160m^2. As for the space heating equipment, water space heating system with panel radiators and vented kerosene heater are popular. As for the ventilation system, exhaust-supply ventilation system is most popular. Exhaust ventilation system is dominant in Fukushima prefecture. But mechanical ventilation in each room is used in more than half houses in Aomori Prefecture. These differences reflect the home builder's design principle.
Pattern of using the heating system: The heating systems tend to be used 50% of the time. The reason why the system was not operated more is that occupants felt warm without space heating.
Pattern of using the ventilation system and indoor air quality: Half the houses in the Tohoku District are ventilated all the time. But, in Aomori and Akita Prefectures, many houses are ventilated intermittently. Room ventilation system tends to be used in these houses. 25% of the occupants noted to feel air pollution from cooking and smoking.
Humidity environment in living room: About 45% of occupants responded that the new house feels drier than in their previous homes.

Figure 2 shows occupants' behavioral change in new house. 60% of occupants responded that it is easier to get up in the morning and also easier to go to toilet at midnight. A few occupants stated they wore socks less often and that children and aged people were more active. In regard to occupant's health after moving into a new house, about 40% of homeowners respond that there was a good effect in health, while about 15% of homeowners

Table 1. Number of respondents

Investigated region		Delivery	Respondents
Tohoku District	Aomori Pref.	107	72
	Iwate Pref.	83	25
	Akita Pref	197	100
	Yamagata Pref.	41	14
	Miyagi Pref.	158	43
	Fukushima Pref.	61	49
Total		647	303

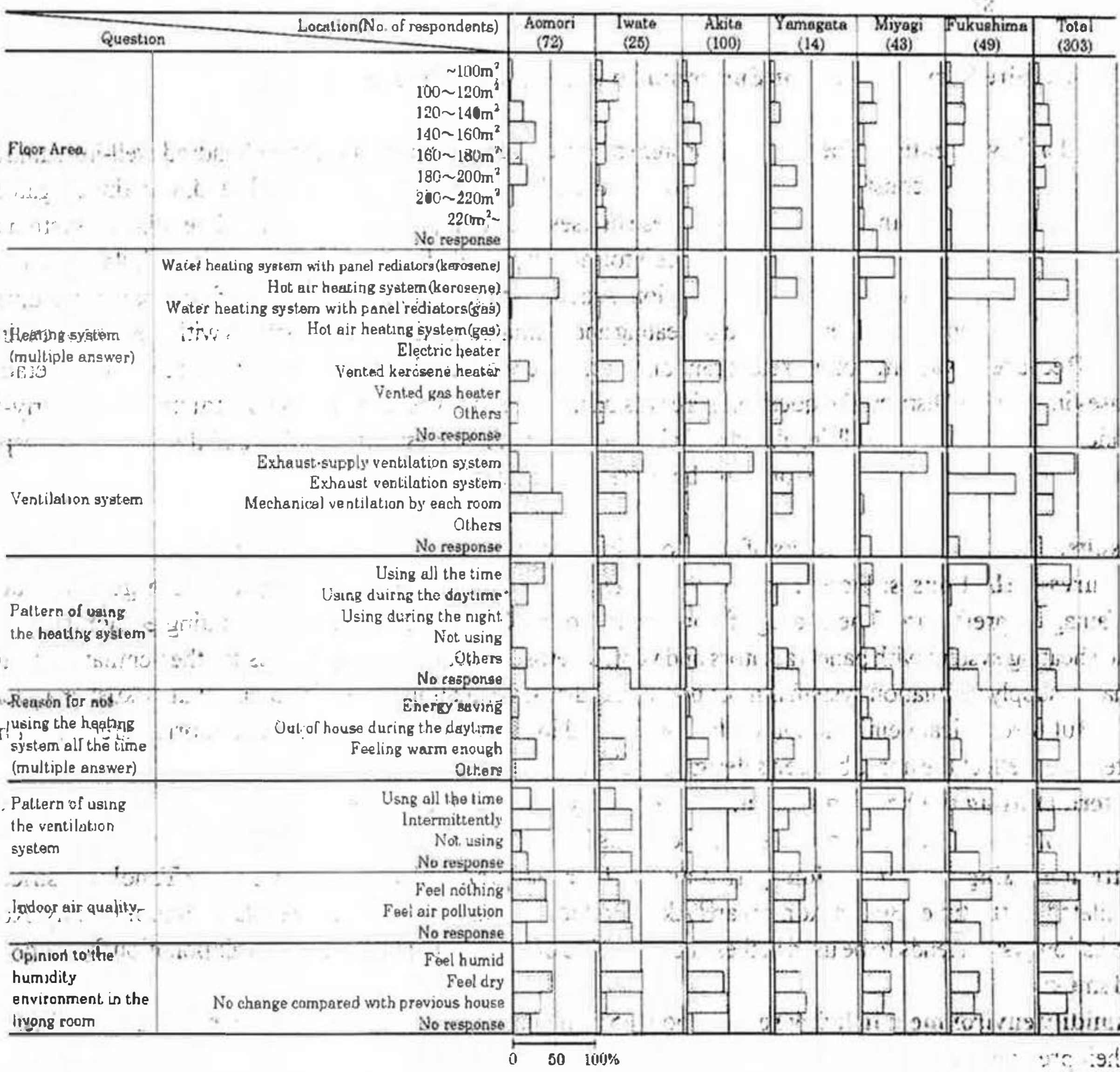

Figure 1. Outcome of questionnaire survey for winter inddor environment

say they developed a health problem. Many respondents say they wore less likely to catch a cold. A few replies indicated that neuralgia, lumbago and stiff shoulders were cured. On the other hand, occupants pointed to dryness of nose, throat and skin.

Field Measurement of Indoor Temperature and Humidity During Winter

Description of Houses Measured and Measurement Procedure. The indoor temperature and humidity of 16 units of well-insulated and airtight houses was investigated in Sendai and Morioka, which are in Miyagi Prefecture and Iwate Prefecture, respectively. The latitude of Sendai and Morioka are 38°16' and 39°42', respectively. The mean outdoor temperatures of Sendai and Morioka are 1.3°C and -1.9°C in February, respectively. The houses investigated were selected randomly from the respondents of questionnaire survey, which told that there are some problems related to dryness. Table 2 describes the houses measured. All houses are wood-

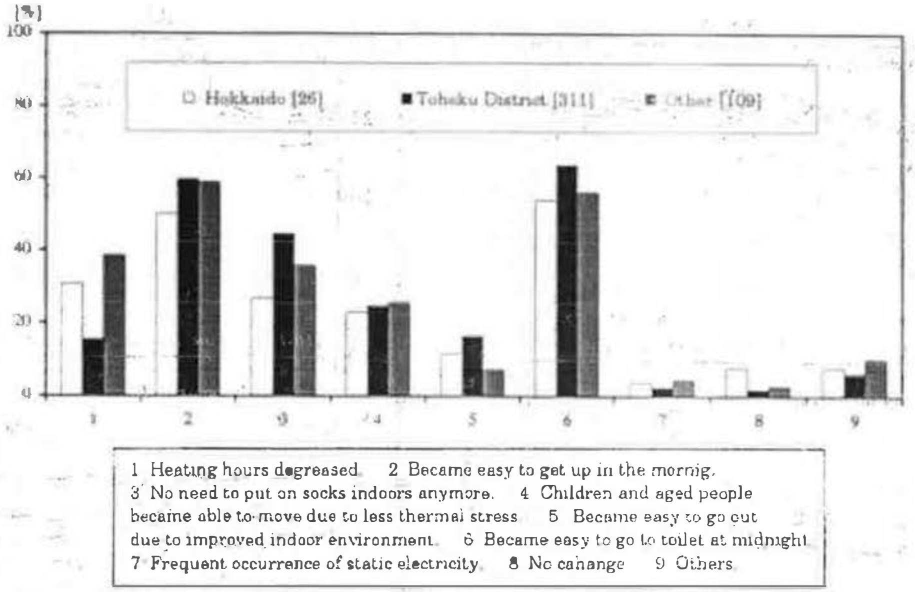

Figure 2. Changes of occupant's behavior in new houses during winter

Table 2. Description of houses measuered

No.*	Completion	Floor Area	Thermal Insulation(mm)			Main Heating System	Supplementary Heating	Cooling System	Family Numbers
			Wall	Floor	Ceiling				
1	1992	182	100	100+30**	200	central / heat pump	electric heater, kotatsu	○	5
2	1989	124	100	150	200	central / circulator	kotatsu	×	4
3	1991	196	100	50+30**	100	central / circulator	electric heater	○	5
4	1989	161	40	30	40	central / circulator	electric heater, unvented kerosene heater	×	3
5	1990	117	40	150	200	central / heating panel	kotatsu	×	5
6	1991	164	100	50+25**	100	electric heater	unvented kerosene heater	○	4
7	1989	155	25	25	50+30***	×	unvented kerosene kotatsu	×	5
8	1992	106	40	40	100	F.F. system	electric carpet	×	4
9	-	-	-	-	-	F.F. system	×	○	6
10	1992	151	50	30+50**	200	central / heating panel	×	○	6
11	1992	206	100	88	200	central / heating panel	electric carpet	○	3
12	1989	116	100	100	200	central / heating panel	×	×	5
13	-	-	-	-	-	F.F. system	×	×	4
14	1992	137	50	30+50**	200	central / heating panel	×	×	4
15	1990	105	100	88	200	central / heating panel	×	○	4
16	1991	224	100	88	200	central / heating panel	×	○	3

* No.1~8 are sited in Sendai City, and No.9~16 in Morioka City. : ** Thermal insulation of foundation : *** Thermal insulation of roof
○: equiped, ×: not equiped

frame construction. The floor area of houses is from 105 to 224 m². All houses have insulated walls, ceilings and floors. The thickness of insulation in house no.2, which is the most heavily insulated, is 100 mm for the walls, 150 mm for the ceiling, and 200 mm for the floor. All houses except no.7 have a water space heating system with panel radiators, a vented kerosene heater or an electric heater. House no.7 has an unvented portable kerosene heater and a "Kotatsu" (a Japanese style electric heater which is mounted under a low table covered with a quilt).

The measurements were conducted during February and March, 1994. Temperatures at three points and relative humidity at two points in each house were measured continuously for a week by resistance type-thermometers and data recorder. The measuring points were set in the living room (1.1 m and 5 cm above the floor level) and in a room with a relatively low temperature (1.1 m above the floor level).

Indoor Temperature and Humidity Profiles. Figure 3 shows temperature and humidity profiles of eight houses

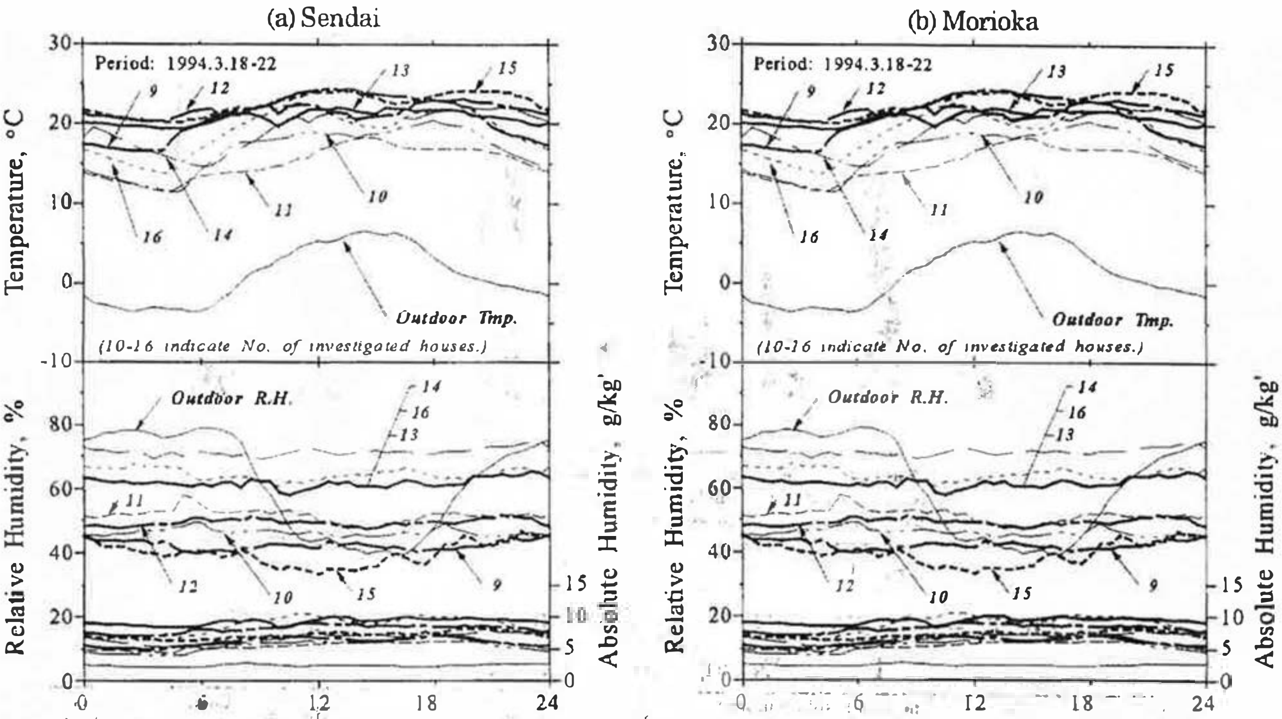

Figure 3. Temperature and humidity profiles averaged for five days during winter in the 16 houses

averaged for 5 days during the winter in Sendai and in Morioka. Except for house no.7, temperatures varied between 10°C and 24°C. In houses no.1, 5, 12, 13 and 15, the space heating system was operated throughout the day. The temperature in these five houses was maintained around 20°C. The temperature of the other houses ranged from 15 to 22°C during the heating time, but after the heating system was turned off, the temperature fell and became 5 to 15°C by daybreak. The temperature of houses no.2 and 7 decreased rapidly. Except for houses no.2 and 15, the relative humidity was 40~70%. Except for houses no.7, 9 and 10, occupants complained of dryness. However, relative humidity measured in these houses was not very low. Possible reasons for occupants' dry feeling may be indoor air pollution (Burt 1997; Sundell & Lindvall 1993).

Comparison of Winter Thermal Environment in Various Houses. Authors et al. have measured the room temperature of 139 houses with different construction features in the Tohoku District (Hasegawa et al. 1987). The thermal environment of the 16 houses reported in this paper was compared to those houses. The room temperature averaged for 3 hours in the evening after supper (p.m.7 ~ p.m.10) was used for comparative analysis of thermal environments. The 155 houses including the well-insulated and airtight houses were categorized into seven groups as shown in Figures 4 and 5.

Figure 4 shows the relationship between the vertical temperature difference and the indoor-outdoor temperature difference. The vertical temperature difference is the temperature difference between 5cm and 1.1m above the floor level. The vertical temperature differences are small in the floor heated insulated houses (Type E) and the 16 houses in this paper (Type F). Except for these houses, the vertical temperature difference is between 3°C and 14°C. The ratio of the temperature difference between 5 cm and 1.1 m above the floor to the indoor-outdoor temperature difference (non-dimensional vertical temperature) ranges from 0 to 0.13, in case of the well-insulated and airtight houses except for one house.

Figure 5 shows the indoor-outdoor temperature difference and the temperature difference relationship

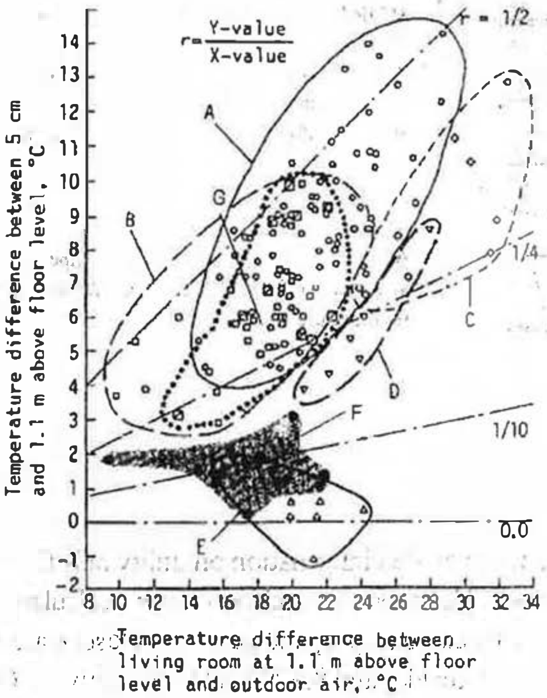

Figure 4. Indoor-outdoor temperature difference and vertical temperature difference in living room during the evening after supper

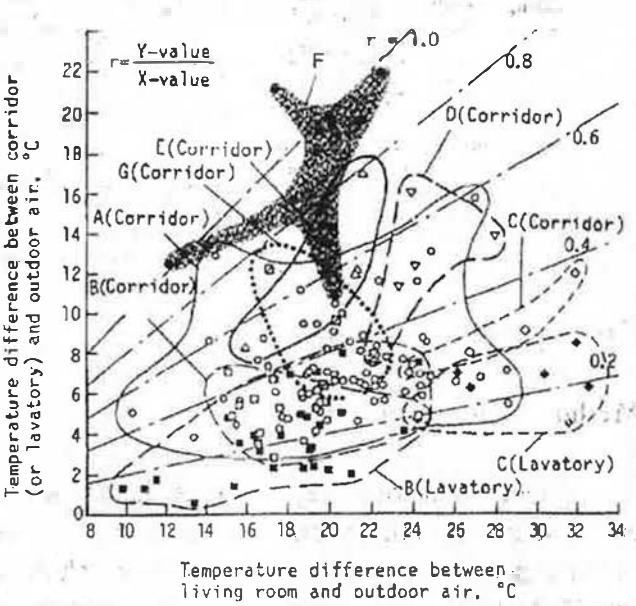

Figure 5. Temperature of living rom and corridor (or lavatory or the room with low temperature) during the evening after supper

- **A:** "PHC Houses" sold by the public housing corporations in the main 8 cities of the Tohoku District(78 houses, constructed in 1968-1979).
- **B:** "Rural Houses" in rural areas of Yamagata Prefecture(30 houses, constructed before 1978)
- **C:** "Village Houses" in a rural village of Iwate Prefecture(9 houses, constructed in 1970-1981).
- **D:** "Insulated Houses" with a space heater in the city of Sendai(7 houses, constructed in 1982-1984)
- **E:** "Floor Heated Insulated Houses" in the city of Sendai(6 houses, constructed in 1982-1984)
- **F: "Well-insulated and Airtight Houses" in the city of Sendai and Morioka(16 houses, constructed in 1989-1992) in this paper**
- **G:** "Multi-Family Houses" constructed of reinforced concrete on the city of Sendai(9 houses, constructed in 1964 and 1971)

between the living room and the bathroom or the corridor or the room with relatively low temperature, averaged for 3 hours in the evening after supper. These temperatures are expressed as the difference from the outdoor temperature. Temperatures in the houses measured were between 11°C and 23°C for relatively low temperature room, when the living room temperature is 20°C. The distribution of the temperature is due to the difference in the levels of thermal insulation and airtightness, and the types of space heating systems employed.

Table 3 shows six indices for indoor thermal environment and their values. Room temperature, vertical temperature difference, globe temperature, and other parameters were taken as indices related to indoor thermal environment. In this table, shown are the ranks of the thermal environment indices of well-insulated and airtight houses measured together with rural houses (group B) located in Yamagata Prefecture and insulated houses (group E) equipped with floor heating. It appears that the decrease of the vertical temperature difference and the improvement of the radiant environment created by thermal insulation. The ranks of five indices of well-insulated and airtight houses are higher than those of rural houses, and close to those of the floor-heated insulated houses.

Table 3. Rank of indicies for indoor thermal environment

Rank			1	2	3	4	5
Living room	Evening family time	Temp. at 1m above floor level	12	15	18	21	24
		Temp difference*1	10	8	6	3	0
		Radiant temp.*2	-3	-2	-1	0	1
	Lowest temp. by daybreak*3		2	6	10	14	18
Bed room temp.*4 (Evening family time)			4	8	12	16	20
Bathroom and corridor temp.*4 (Evening after supper)			2	5	8	11	14

Rural Houses

Well-insulated and airtight houses

Floor heated insulated houses

*1 Temperature difference between 5cm and 1m above floor level.

*2 Radiant temperature in this table represents the difference between the globe temperature and dry-bulb temperature at 1m above floor level.

*3 At the time when the outdoor temperature is 0°C.

*4 At the time when the living room temperature at 1m above floor level is 20°C and outside temperature is 0°C.

Energy Consumption

Method of Investigation

Questionnaire survey mentioned in the previous chapter included information on utility bills for each energy source. Monthly calorific consumption of electricity, gas and kerosene for each house were calculated on the basis of these utility bills. The conversion values of electricity, city gas, propane gas and kerosene are 860 kcal/kWh, 4,200~11,000 kcal/m^3 (different in each area), 12,000 kcal/kg and 8,900 kcal/l, respectively. One-year data were obtained for February, 1993 through January, 1994.

Annual Amount of Energy Consumption

Figure 6 shows the frequency distribution of the annual energy consumption. The number of respondents is 87. The energy consumption ranges from 10 to 48 Gcal, and the mean value is 22.4 Gcal. Figure 7 shows the mean value of total energy consumption for the well-insulated and airtight houses investigated in each prefecture compared with the mean values in all Japan, in Tohoku District and in Hokkaido District in 1993. These values come from a data book (Nakagami 1993). This figure shows that the energy consumption of investigated houses is more than the mean value of ordinary existing houses in Tohoku District, and close to that in Hokkaido District. Because, in the existing detached houses in Tohoku district, only the living room is heated intermittently.

Annual Amount of Kerosene Consumption for Space Heating

Annual kerosene consumption for space heating is calculated from the bills reported on the questionnaire. When kerosene is used for space heating as well as water heating, annual kerosene consumption only for space heating was estimated by subtracting kerosene consumption for water heating from annual one (Sawachi et al. 1994). The kerosene consumption for water heating is estimated using the value of non-heating season in June to September. The number of respondents is 115. Figure 8 shows the frequency distribution of annual kerosene consumption for space heating. It ranges from 250 to 3000 liters, and the mean value is 1269 liters. Figure 9 shows the kerosene consumption of each house investigated and the mean value of the ordinary existing detached houses in local cities in Tohoku district (Yoshino et al. 1997). The well-insulated and airtight houses consumed more kerosene than the existing detached houses because of the increase in heated floor area and heating hours.

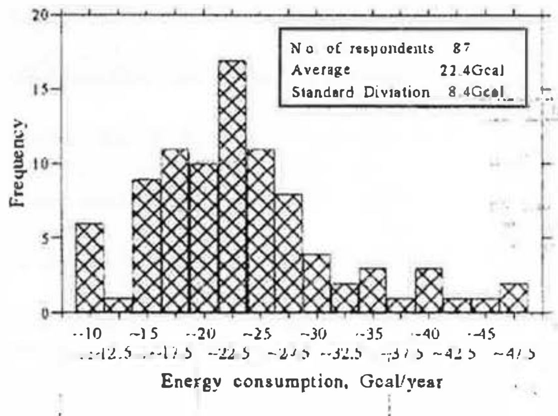

Figure 6. Frequency distriution of annual energy consumption

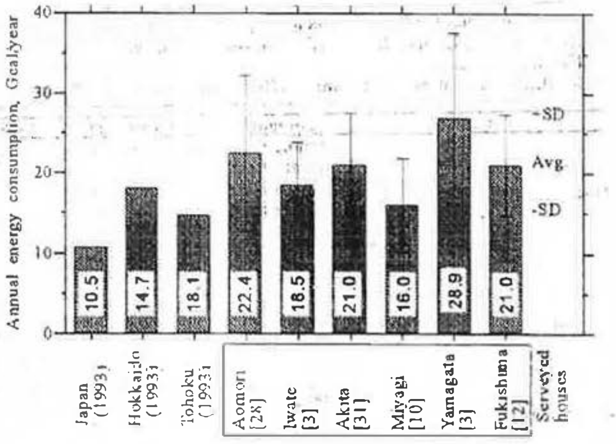

Figure 7. Comparison of annual energy consumption

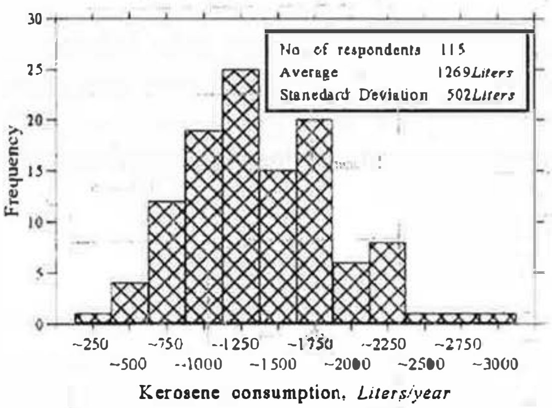

Figure 8. Frequency distriution of kerosene consumption for space heating

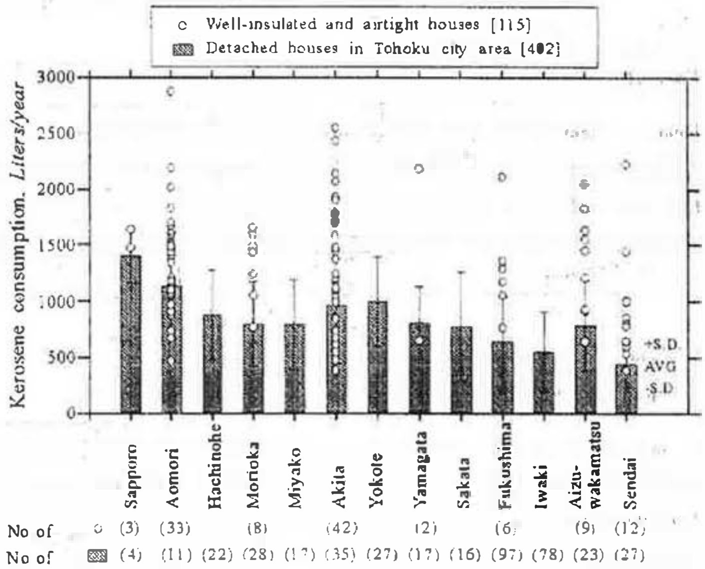

Figure 9. Comparison of annual kerosene consumption for space heating

In Aomori and Akita, the amount of kerosene consumed in well-insulated and airtight houses ranges from 500 to 3000 liters, which is from 0.5 to 2 times that of the ordinary existing houses.

Analysis of Relationship between Kerosene Consumption for Space Heating and Influencing Factors by a Multi-Regression Method

A multi-regression analysis method was applied in order to clarify the relationship between kerosene consumption for space heating and influencing factors, such as indoor thermal environment, building components, heating patterns and equipment. Data sets for 85 houses selected from the houses shown in the Figure 8 were used for the analysis. Figure 10 shows the calculated results. For the pattern heating, for example, 47 houses used the heating system all the day and 39 houses used the system intermittently. The category weights of those two groups are 113.2 liters and -140.1 liter, respectively, which means that the influence of heating hours on

Objective variable : Kerosene consumption for space heating
Average 1300 Liters, Standard Deviation 507 Liters
No. of respondent 85
Multiple correlation coefficient 0.75 (contribution 0.56)

Item	Category	Number
Area	Aomori Prefecture	30
	Iwate Prefecture	6
	Akita Prefecture	27
	Yamagata Prefecture	2
	Miyagi Prefecture	8
	Fukushima Prefecture	12
Foor area (m^2)	~120	15
	120~140	14
	140~160	19
	160~180	13
	180~200	14
	~200	11
Construction	Wooden(conventional)	53
	2×4	20
	Wooden(new type)	13
Thickness of thermal insulation(mm)	~50	12
	50~100	19
	100~	55
Material of window sash	Plastic	75
	Wooden	8
	Others	3
No. of glass	Double	83
	Triple	3
Heating system	With panel radiators	52
	Hot-air heating	12
	Vented kerosene heater	22
Heating period	~5 months	21
	5~6 months	25
	6~7 months	30
	7 months ~	9
Pattern of heating usage	all the time	47
	Intermittently	39
Heating floor area	Entire house	73
	Not entire house	13
Feel cold in the house?	Yes	27
	No	59
Supplementary heating	Used	79
	Not used	7
No. of family	~3	29
	4~5	47
	6~	10
Annual income (million yen)	~600	24
	600~800	18
	800~1000	19
	1000~1400	19
	1400~	6

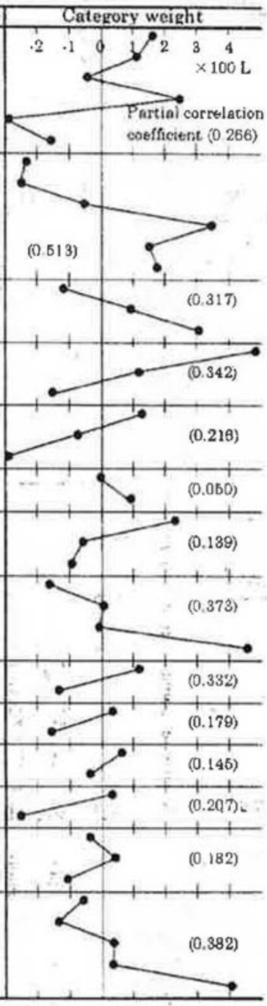

Figure 10. Result of calculation by a multi-regression analysis method

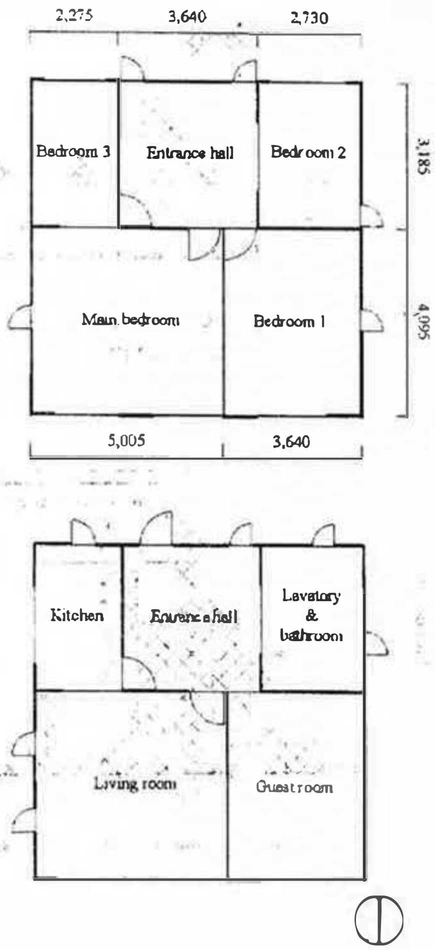

Figure 11. House plan for calculation of heating load

kerosene consumption is great. The partial correlation coefficient of floor area, annual income, the heating period, insulation thickness, patterns of heating usage are comparatively greater in all factors, so these factors tends to influence kerosene consumption. The analysis indicates that thermal insulation is very effective for decreasing kerosene consumption.

Numerical Analysis of Heating Load

Calculation Procedure

In order to study the effect of improvement of building envelope performance on space heating load, the calculation has been done using a model which takes account of the multi-zone heat transfer and air flow. This calculation model is divided into two parts. These are thermal model and airflow models. The thermal model calculates the internal surface temperature of building envelope, room temperatures, the heating load and the amount of heat transfer through walls using the response factor method. Airflow model calculates multi-zone air infiltration by the airflow network model (Yoshino 1993).

Input Data for Calculation

Figure 11 shows a house plan for calculation, which is a standard house of Architecture Institute of Japan proposed by Udagawa (Udagawa 1985). The model house has 10 rooms including an attic space. Table 4 shows the assumption for calculation. The parameters used for the calculation are five level of the envelope performance, five regions and two types of heating schedule. Standard weather data were used. Table 5 shows the conditions for 33 cases. The envelope performances are decided in accordance with the different climatic area classification (Region I to VI) described in the new version of "The Law Concerning the Rationalization of Energy Use" issued in 1994 in Japan. Table 6 shows the levels of thermal insulation, airtightness and windows for Region III including Sendai and Fukushima. Two heating schedules are presumed as follows. (1) A living room and a kitchen are heated from 6 a.m. to 11 p.m. The bedroom is heated from 7 p.m. to 11 p.m. and room

Table 4. Assumption for caluculation of heating load

Structure, story	Wooden, two-story
Floor area, Number of rooms, Number of walls	126m^2, 10, 124
Thermal insulation (glass wool) Finishing of floors	Table 6 (example for region III) Carpet, *tatami* mat (guest room)
Heat capacity of furniture	4.5 kcal/m^2°C
Effective area of windows, Window ratio to wall, Window glass	21.5m^2, 14.5%, Double glazing
Family members	Parents and two children
Schedule of central ventilation system Schedule of ventilation fan in the kitchen	24 hours (supply-exhaust system, total 240 m^3/h) 6:00~7:00, 17:00~18:00 (200 m^3/h) 12:00~13:00 (100 m^3/h)

Table 5. Conditions for calculation of heating load

Envelope performance Level	Level 1	Level 2	Level 3	Level 4	Level 5
Heating schedule (1)*	Sapporo, Akita, Morioka, Sendai, Fukushima				
Heating schedule (2)**	Akita, Morioka, Sendai, Fukushima				

* Continuous operating of space heating for the entire house
** Intermittent operating of space heating only for a living room

Table 6. Building envelope performance level (Region III)

Envelope perfomance level.	Thickness of thermal insulation [mm]			Airtightness	Type of Glass
	Ceiling	Wall	Floor	a A'[cm^2/m^2]	
Level 1	50(10K)	25(10K)	25(10K)	12.5	Single
Level 2	65(10K)	45(10K)	40(10K)	7.1	Double
Level 3	100(10K)	100(10K)	100(10K)	4.1	Double
Level 4	200(10K)	100(16K)	100(16K)	1.25	Double
Level 5	400(10K)	150(32K)	150(32K)	0.41	Triple

( ) : density of glass wool

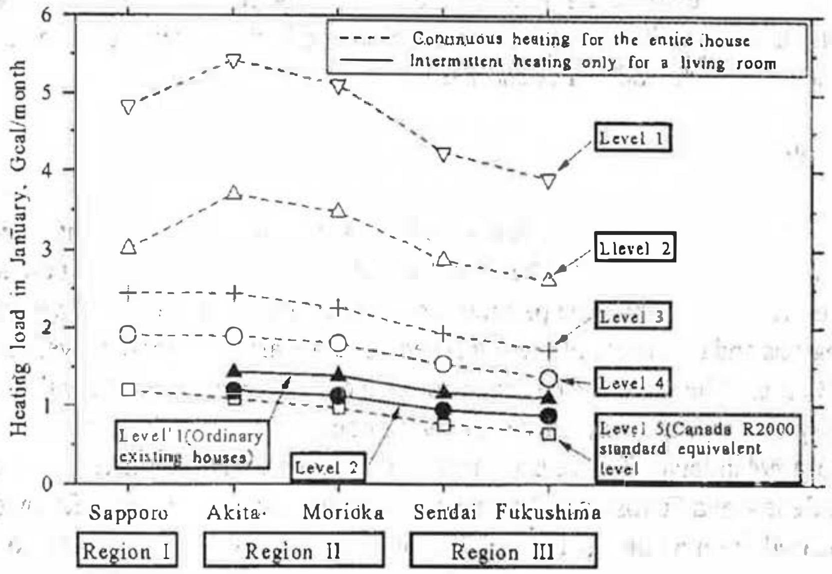

Figure 12. Calculated result of space heating load for one month

temperature is maintained at 20 °C during the space heating operation and at 16 °C during the other time. (2) Only the living room is heated from 6 a.m. to 11 a.m. and from 5 p.m. to 11 p.m. and room temperature is maintained at 20 °C during the heating operation.

Calculated Results

Figure 12 shows the calculated results which illustrate the relationship between the space heating load and the level of envelope performance in each city for January. In each city, the heating loads decrease as the level of envelope performance improves. In the case of the entire rooms heated all day, the heating load of Level 4 is about 1.7 times that of ordinary existing house equivalent level (Level 1 - Heating schedule (2)). The heating load of Level 5(Canada R2000 standard equivalent level) is about 0.6 times that of ordinary house. It can be expected that if the houses have thermal insulation comparable to R2000 houses in Canada, indoor environment will be thermally comfortable with less energy consumption than the ordinary existing houses.

Conclusions

1) Indoor environment during the heating season of well-insulated and airtight houses was more thermally comfortable, compared with that of the ordinary existing houses. Some occupants complained of dryness of indoor air in winter. There is possibility of other reasons for occupants□Edry feeling, which may be indoor air pollution. This problem should be investigated further.
2) The energy consumption of well-insulated and airtight houses investigated is more than the mean value of ordinary existing houses in Tohoku District, and close to that in Hokkaido District. Also, these houses investigated consumed more kerosene than the existing detached houses, because of increase in heated floor area and heating hours.
3) To clarify the relationship between kerosene consumption for space heating and influencing factors, a multi-regression analysis method was applied. The factors which influence the dispersion of kerosene consump-

tion are floor area, annual income, the heating period, insulation thickness, patterns of heating usage. The analysis indicates that thermal insulation is very effective for decreasing of kerosene consumption.

4) Computer simulations reveal that the well-insulated and airtight houses in the Tohoku District consume more energy for space heating than ordinary existing houses, in which only the living/dining room is heated. The results also show, that it would be possible to keep a comfortable indoor environment with less energy consumption than the ordinary houses, if the houses had insulation comparable to R2000 houses in Canada.

Reference

Burt, T.S. 1997. "Dry Air and Sick Building Syndrome." *In proceedings of Healthy Buildings/IAQ '97*, 2:367-372.

Hasegawa, F. and Yoshino, H. 1987. "Investigation on winter indoor temperature of various types of houses in the Tohoku District." *Journal of Architecture, Planning and Environmental Engineering* 371: 18-26.

Nakagami, T. 1993. "Energy consumption of dwellings", *Private report of Jyukankyo Research Institute*.

Sawachi, T., Bokgaki, K., Yoshino, H., Suzuki, K., Akabayashi, S., Inoue, T., Ohno, H., Matsubara, N., Hayashi, T. and Morita, D. 1994. "Energy consumption for different uses in dwelling and its estimation formulas (Part I), *Journal of Architecture, Planning and Environmental Engineering* 462: 41-48.

Sundell, J. and Lindvall, T. 1993. "Indoor Air Humidity and Sensation of Dryness as Risk Indicators od SBS." *Indoor Air* 3: 382-390.

Udagawa, M. 1985. "Proposition of the standard model of a house for energy calculation", The 15th Symposium of Thermal Environment: 23-33.

Yoshino, H. and Hasegawa, K. 1997. "Change in regional characteristics of winter thermal performance and occupant's behavior of detached houses in Tohoku city area for 10 years." Journal of Architecture, Planning and Environmental Engineering 499: 1-7.

Yoshino, H., Hasegawa, F., Nagatomo, M., Ishikawa, Y. and Toyohara, N. 1993. "Analysis on improvement of residential building performance by multizone thermal and airflow model." ASHRAE Transactions. DE-93-7-5: 721-729