INVESTIGATIONS ON THE EFFECTS OF AIRTIGHT PERFORMANCE IMPROVEMENT AND ENERGY CONSUMPTION OF INSULATION RETROFIT IN DETACHED HOUSES

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ABSTRACT

Recently, insulation retrofits of existing houses have been thought to be one of the effective measures from the viewpoint of global warming prevention. However, the overall reduction effects of environmental loads by the insulation retrofits have not yet been clarified. This study intends to accumulate basic data concerning the insulation retrofits and to promote the energy saving of existing houses.

The environmental performances of 4 detached wooden houses in *Tohoku* region, Japan before and after the insulation retrofits were investigated. The indoor thermal environments, energy consumption, and performances of insulation and air tightness before and after the retrofit were analyzed. In addition, the effects of insulation retrofits were clarified.

The heat loss coefficient ("Q") and the equivalent air leakage area in proportion to the floor area ("C") were calculated in each house before and after the retrofit. After the retrofit, the values were changed to $Q=1.2\ W/m^2K$ & $C=2.1\ cm^2/m^2$ in house_A and $Q= 1.5W/m^2K$ & $C=1.1\ cm^2/m^2$ in house_B.

During winter, in house_C, temperature differences between the living room and other rooms went up to 20 ℃ before the retrofit. After the retrofit, temperature differences were limited about 5 ℃, and the indoor vertical temperature difference was 2.5 ℃at a maximum.

In house_A, city gas was used twice and once a day before and after the retrofit respectively. The average values of city-gas consumption were 10 kW and 8 kW before and after the retrofit respectively.

Comparing annual energy consumption before and after the retrofit, in houses_A and B, energy consumption were decreased by 35% and 44% after the retrofit respectively. However, in house_D, energy consumption was increased by 42% because the insulation retrofit had partial effect.

KEYWORDS

Insulation retrofit, Air tightness, Energy consumption, Indoor thermal environment, Field measurement, Detached house

INTRODUCTION

The first commitment period of the Kyoto Protocol started in 2008. The government set the medium-term target for reducing greenhouse gas emissions in Japan; reducing emissions by 25% compared with 1990. Recently, insulation retrofits of existing houses have been thought to be one of the effective measures from the viewpoint of global warming prevention. In Japan, there are many existing houses without enough thermal insulation. However, the overall reduction effects of environmental loads by the insulation retrofits have not yet been clarified. Therefore, this study intends to accumulate basic data concerning the insulation retrofits and to promote the energy saving of existing houses based on the methods and effects of energy saving for retrofitted houses.

The authors investigated the environmental performances of 4 detached wooden houses in *Tohoku* region, Japan before and after the insulation retrofits [1]-[4]. In this paper, the indoor thermal environments, energy consumption, and performances of insulation and air tightness before and after the retrofit were analyzed. The effects of insulation retrofits were clarified.

OUTLINE OF INVESTIGATED HOUSES

The location of the investigated houses is shown in Figure 1. The description of each house is shown in Table 1.

In houses_A, B and C, the whole house was renovated while the occupants' living there. Heat insulators were added to the existing walls after the exterior materials were removed, and the interior materials remained except some changed parts. In house_A, a push-pull ventilation fan with total heat exchanger was set in each room during the retrofit. All rooms can be warmed up by existing heating panels, and the heat source is water heated by a co-generation system (gas engine type). Moreover, one month after the retrofit, the photovoltaic system was installed in house_A. In house_B, all rooms can be heated by new hydronic heating panels and existing heating equipments. In house_C, there is an existing air conditioner, and hydronic heating panels were set after the retrofit. In both houses_B and C, the heat source of hydronic heating panels is water heated during night time. Hot water is supplied by an air refrigerative heat pump boiler, and the pull ventilation system is used.

In house_D, heat insulators were partially added to only the walls and the base. The household equipments are the existing ones.

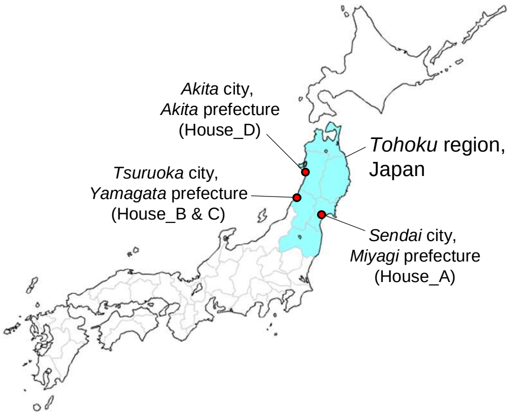

Figure 1. Location of investigated houses.

	House_A		House_B		House_C		House_D	
	Before	After	Before	After	Before	After	Before	After
Site	Sendai, Miyagi		Tsuruoka, Yamagata		Tsuruoka, Yamagata		Akita, Akita	
Household size	4	3	3		3	7	2	
Completion year	1984	2010	1991	2008	1980	2007	1995	2010
Floor area	124.2 m^2		141.2 m^2	164.0 m^2	229.4 m^2	244.3 m^2	134.3 m^2	
Heat loss coefficient	3.6 W/m^2K	1.2 W/m^2K	4.5 W/m^2K	1.5 W/m^2K	8.3 W/m^2K	1.7 W/m^2K	2.3 W/m^2K	2.1 W/m^2K
Equivarent leakeage area	3.6 cm^2/m^2	2.1 cm^2/m^2	8.2 cm^2/m^2	1.1 cm^2/m^2	--	1.2 cm^2/m^2	--	2.1 cm^2/m^2
Space heating*	Hydronic panel heater, AC		FF type stove heater, Hydronic heater, AC	Hydronic panel heater, Hydronic heater, AC	FF type stove heater, Fan heater	Hydronic panel heater, AC	FF type stove heater, Hydronic heater, AC	
Hot water supply**	Gas engine co-generation system		Combination boiler	Electric HP water heater	Combination boiler	Electric HP water heater	Combination boiler	
Ventilation type (in living space)	--	Push-pull (heat exchanger:62%)	Pull		--	Pull	Pull	
Energy source	City gas, electricity		Oil, electricity	Electricity	Oil, city gas, electricity	Electricity	Oil, city gas, electricity	

*FF type: Forced draught balanced Flue type, AC:Air Conditioner **HP:Heat Pump

Table 1. Description of investigated houses.

PERFORMANCES OF INSULATION AND AIR TIGHTNESS

The heat loss coefficient (“Q”) and the equivalent air leakage area in proportion to the floor area (“C”) were calculated in each house before and after the retrofit.

The Q values were calculated from the design documents of each house [5]. In house_A, the Q value before and after, respectively is 3.6 W/m^{2}K and 1.2 W/m^{2}K. With the retrofit, 100mm insulation boards (polystyrene foams or phenolic foams) were added to the existing walls. 400mm glass wool and 100mm polystyrene foams were added to the ceiling and floor respectively. As for the windows, Low-E triple-pane glasses and insulated plastic frames are used for the retrofit.

The Q values were changed from 4.5 W/m^{2}K to 1.5 W/m^{2}K in house_B, and from 8.3 W/m^{2}K to 1.7 W/m^{2}K in house_C. In the wall and ceiling, phenolic foams & high performance glass wool were added. Polystyrene foams were added to the existing base, and Low-E double-pane glasses and plastic frames are used after the retrofit.

In house_D, the Q value before and after, respectively is 2.3 W/m^{2}K and 2.1 W/m^{2}K. The insulation performance was not improved so much because added heat insulators were partial.

The C values were measured by the depressurization method using the airtight instrument (Figure 2). The C values were changed from 3.6 cm^2/m^2 to 1.2 cm^2/m^2 in house_A, and from 8.2 cm^2/m^2 to 1.1 cm^2/m^2 in house_B. In houses_C and D, the C values were not measured before the retrofit. After the retrofit, that is 1.2 cm^2/m^2 in house_C and 2.1 cm^2/m^2 in house_D.

Figure 2. Measuring air tightness.

AIRTIGHT CONSTRUCTION METHODS IN EACH HOUSE

Examples of airtight construction methods in each house are shown in Figure 3.

In house_A, insulation boards were added to the existing walls and floor from outside. In houses_B and C, glass wools were filled in the walls and insulation boards were added from outside. Then air tightness was ensured by the added insulation boards in each house. For example, airtight sheets were applied to the walls before insulation boards were added, and the connections of insulation boards were sealed with the airtight tape. The connections between the window frames and insulation boards were also sealed. In house_A, after that, damp-proof membranes were added from outside, and the vent layer was made.

Moreover, in houses_B and C, the gaps between insulation boards and the groundsill / roof rafters were filled with the foam insulation in the base / the attic. In house_A, the gaps between insulation boards and the base / pipes etc. were filled with urethane foam in the underfloor space. The foam insulation were also used places beyond the reach.

Figure 3. Examples of airtight construction methods.
(Left:house_A, Middle:house_B, Right:house_C)

PROFILES OF INDOOR THERMAL ENVIRONMENT IN WINTER

Temperature and humidity of each house in winter were measured. The changes of outdoor and living-room temperatures during 1 week in winter before and after the retrofit are shown in Figure 4. (In house_D, before the retrofit, the data for 5 days are used.) The data interval is 30 min. In house_B, the measurement was not carried out before the retrofit.

In houses_A and D, there were little differences of living-room temperatures before and after the retrofit. This is because thermal insulation performances before the retrofit were not so low, and the same heating equipments were used before and after the retrofit in houses_A and D.

In house_B, though not in comparison with temperatures before the retrofit, living-room temperature after the retrofit exhibited relatively less volatility than temperatures in other houses. In house_C, while living-room temperature fluctuated widely before the retrofit, the fluctuation range after the retrofit was the smallest in all houses.

Next, the measurement result in house_C is shown in detail. In house_C, temperature and humidity were measured in 6 places (Living-room, Bedroom, Guest-room, Toilet, Hallway, Outdoor), and the measurement interval was 10min. The profile of temperature in each room during 3 days in winter before and after the retrofit is shown in Figure 5.

Before the retrofit, temperature differences between living-room and other rooms were very large from morning (around 7 a.m.) till midnight, and went up to 20 ℃. Though living-room temperature varied around 22 ℃ in heating equipments operation, temperatures of other rooms fluctuated just like outdoor temperature. Moreover, after turning off heaters, living-room temperature went down soon.

On the other hand, after the retrofit, indoor temperatures varied from 14 ℃ to 21 ℃, and temperature difference between rooms was small.

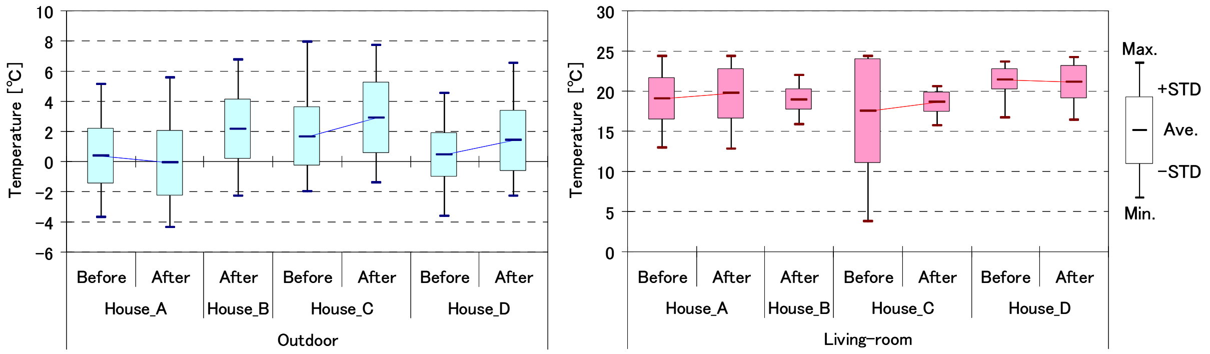

Figure 4. Changes of outdoor and living-room temperatures in winter.

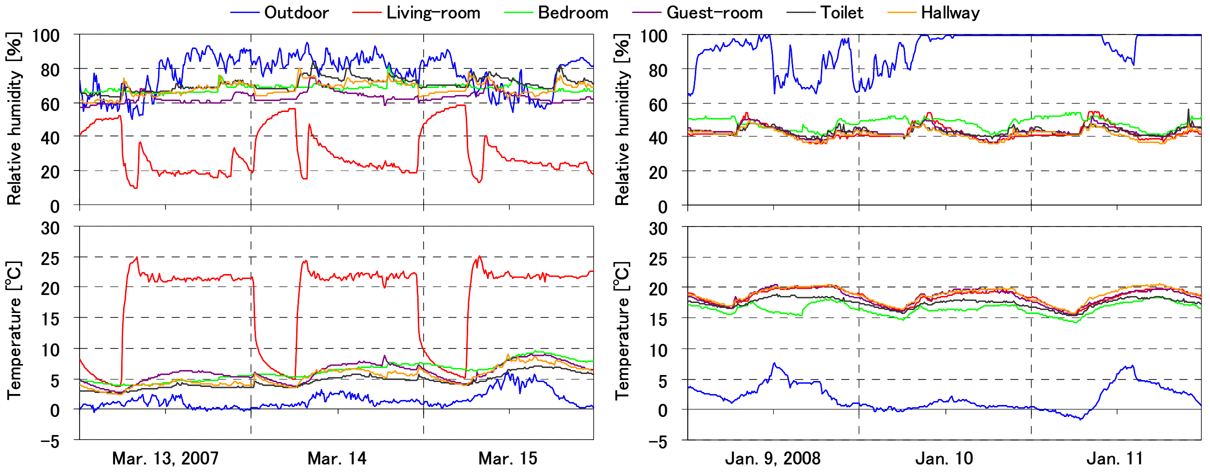

Figure 5. Profiles of temperatures in house_C (Left:before, Right:after).

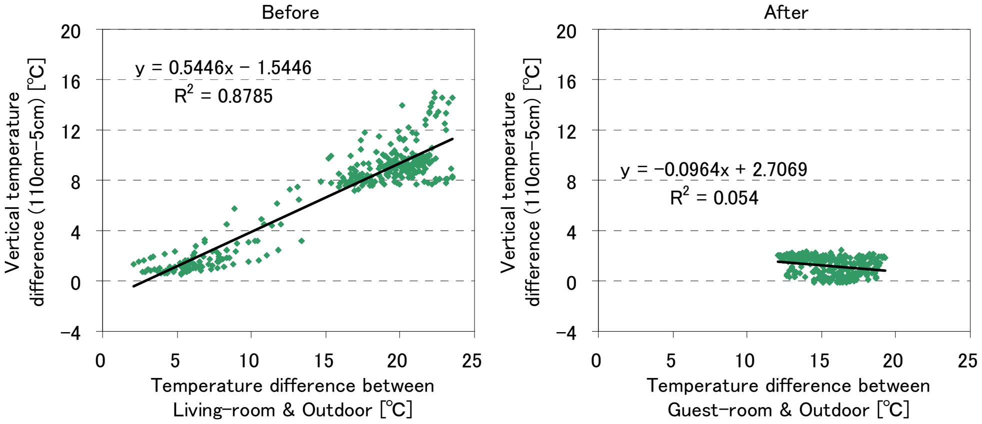

Figure 6. Correlations between two temperature differences in house_C.

The correlations between two temperature differences during 1 week in winter before and after the retrofit are shown in Figure 6. In this figure, the horizontal axis shows temperature difference between indoor and outdoor. The vertical axis shows indoor vertical temperature difference between 5cm and 110cm above the floor. The data interval is 30 min.

The vertical temperature difference was 15 ℃ at a maximum in house_C. Before the retrofit, the value of coefficient of determination (R^2) is 0.88, so outdoor temperature contributed to increment of vertical temperature difference. After the retrofit, the vertical temperature difference was 2.5 ℃ at a maximum. The upper limit of vertical temperature difference (0.1m-1.1m above the floor) is 3 ℃ in ISO 7730 [6]. Moreover, the value of coefficient of R^2 is very small, and outdoor temperature and vertical temperature difference have no correlationship.

PROFILES OF ENERGY CONSUMPTION IN WINTER

In house_A, energy consumption in winter was measured in detail. The profiles of energy consumption and temperatures during 3 days in February before and after the retrofit are shown in Figure 7 and Figure 8 respectively. The data interval was 15 min. 3 day profiles when daily-averaged outdoor temperatures were similar before and after the retrofit are compared.

Before the retrofit, outdoor temperature changed from 0 ℃ to 13 ℃, while living-room temperature varied from 16 ℃ to 24 ℃. Space heating was operated twice a day in the morning and evening. Living-room temperature rose by 5 ℃ during space heating. Bedroom temperature, which varied from 15 ℃ to 21 ℃, was a little lower than living-room temperature. The co-generation system (“CGS”) generated electricity (max. 1 kW) when city gas and electricity were used so much.

In contrast, outdoor temperature widely varied from -4 ℃ to 17 ℃ after the retrofit. But living-room temperature changed from 18 ℃ to 25 ℃ and bedroom temperature changed from 17 ℃ to 21 ℃. Though space heating was not operated so much in the morning, indoor temperature change was smaller than that of before retrofit, and room temperature was kept more than 17 ℃. The photovaltaic system (“PV”) generated electricity (max. 2.4 kW) during the day.

City gas was used twice a day before and once a day after the retrofit respectively. The average values of city-gas consumption were 10 kW and 8 kW before and after the retrofit respectively.

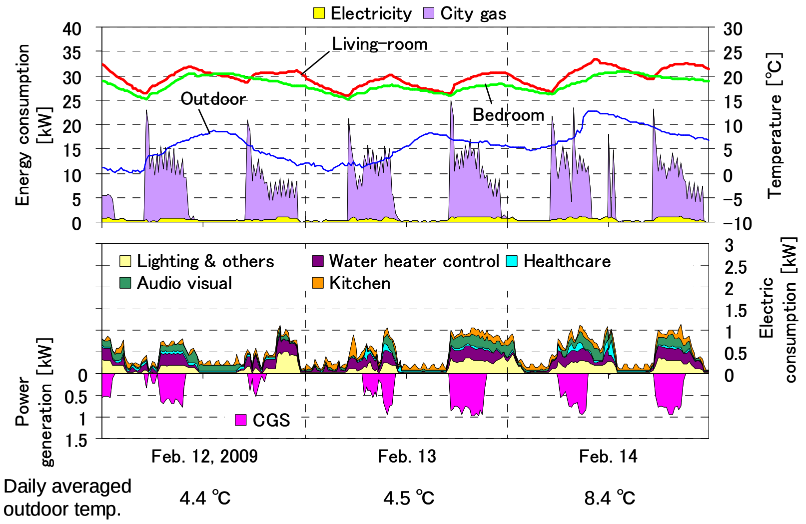

Figure 7. Profiles of energy consumption in house_A before the retrofit.

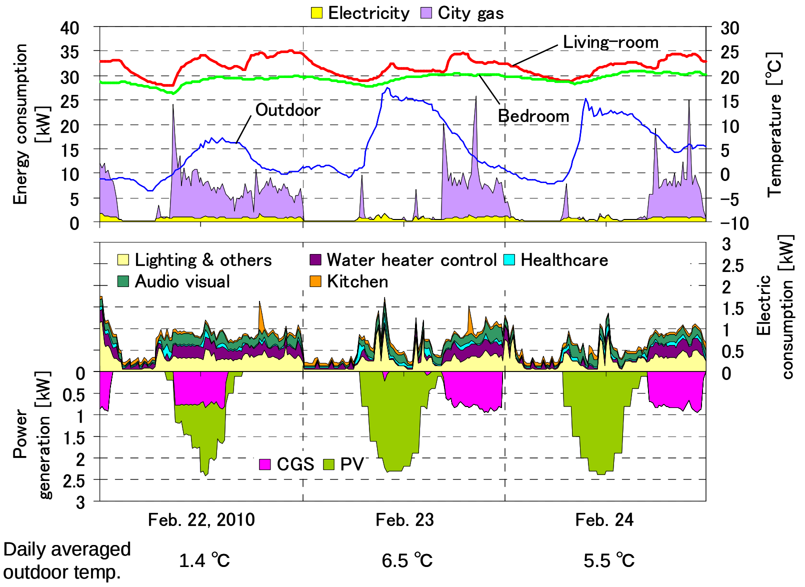

Figure 8. Profiles of energy consumption in house_A after the retrofit.

Based on the comparison of temperature change and city-gas consumption before and after the retrofit, it can be stated that insulation retrofit made the change of temperature smaller and decreased the city-gas consumption.

COMPARISON OF ANNUAL ENERGY CONSUMPTION BEFORE AND AFTER THE RETROFIT

Annual energy consumption in each house before and after the retrofit is shown in Figure 9. This was calculated by the receipts of energy bill (oil, city gas and electricity), and measurement results was considered in house_A. Energy coefficients of oil, city gas and electricity are shown in Table 2 [7].

In house_A, energy consumption decreased by 23% (24.8 GJ) after the retrofit. The power generation from CGS and PV system was 76% of the electric consumption ("Others" in Figure 9) after the retrofit. Considering the power generation as reduction of energy consumption, energy consumption decreased by 35% (35.7 GJ).

In house_B, the whole energy consumption decreased by 44% (48.4 GJ) after the retrofit. This is especially for space heating with energy consumption decreased by 33% (19.7 GJ).

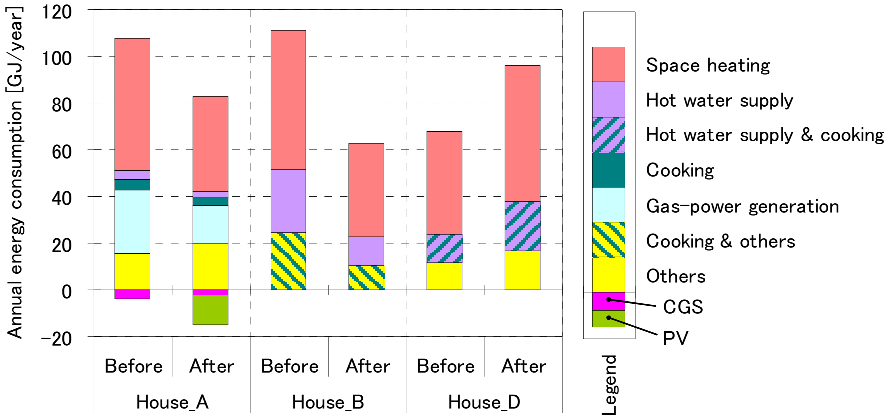

Figure 9. Annual energy consumption before and after the retrofit.

	Basic unit	Energy coefficient
Oil	L	37.26 MJ/L
City gas	m^3	46.05 MJ/m^3
Electricity	kWh	3.6 MJ/kWh

Table 2. Energy coefficients.

Hence, the performance of thermal insulation, energy efficiency of equipments and occupants' awareness of energy saving were improved after the retrofit.

In contrast, the whole energy consumption increased by 42% (28.5 GJ) after the retrofit in house_D. The space heating alone, energy consumption increased by 33% (14.5 GJ). After the retrofit, though reduction of energy consumption for space heating was expected, the insulation retrofit was ineffective for some parts of the house. Usually heat losses from the windows are large, so the athermalize of the windows may be more effective than that of the walls and the base.

CONCLUSION

This paper provided measurement results of 4 houses before and after the insulation retrofit in Tohoku region, Japan.

About profiles of indoor thermal environment and energy consumption in winter,

- In houses_A and D, there were little differences of living-room temperatures between before and after the retrofit. In houses_B and C, the fluctuation ranges were small after the retrofit.
- In house_C, temperature differences between rooms was small after the retrofit, and the vertical temperature difference was 2.5 ℃ at a maximum.
- In house_A, heating equipment operation hours and daily consumption of city gas decreased after the retrofit.

About annual energy consumption,

- In house_A, considering the power generation by CGS and PV as reduction of energy consumption, energy consumption decreased by 35% (35.7 GJ). In house_B, energy consumption decreased by 44% (48.4 GJ) after the retrofit.
- In house_D, energy consumption increased by 42% (28.5 GJ) after the retrofit. This is because the insulation retrofit was ineffective for some parts of the house.

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