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EFFECTIVENESS OF SUBTERRANEAN HEAT USE IN AN EARTH TUBE COMMUNITY HOUSE

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ABSTRACT

This study involves a year-round measurement survey of outside air and indoor outlet temperature and humidity for a community house with an earth tube system constructed in Japan. The effectiveness of using subterranean heat in a house in the Hokuriku region is examined by calculating heat extraction in summer and heat addition in winter. The main features of this research are as follows: (1) an earth tube system (total length approximately 125 m) is installed beside a house at a depth of 2 m to reduce excavation costs; (2) measurements are taken under the condition of a ventilation rate of 0.33times/h (ventilation air volume, approximately 260 m^3/h), which represents a fresh air load reduction and (3) the sensible and latent heat of the heat extraction in summer and the heat addition in winter under Hokuriku climate conditions in Japan are analyzed. The thermal effect of an earth tube system in summer is larger than in winter. The peak in heat extraction by the earth tube system was -1722 MJ/month in July and the latent heat portion of -906 MJ/month has exceeded the sensible heat portion of -866 MJ/month.

1. INTRODUCTION

In recent years, as the need for the development of low-carbon architecture increases, practical use of the natural energy that surrounds buildings is attracting attention. Earth tube systems make use of one such natural energy, subterranean heat. These systems reduce the fresh air load by introducing outside air through tubes that pass beneath the ground before blowing the air indoors.

Preliminary calculations carried out using the formulas for periodic heat conduction in semi-infinite solids (Hasegawa, 1965) show that the depth at which subterranean temperature remains at roughly the annual mean outside air temperature is more than 5 or 6 m, depending on the values used for the thermal conductivity of the soil and the outside air temperature fluctuation in the region. However, using this depth for earth tube systems in real houses is difficult because of

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excavation costs and deterioration of the bearing capacity of the ground. The depth up to which sheet piling is not necessarily required during excavation is usually 2 m at most, depending on the actual conditions of the construction site.

Therefore, in the present research study, a community house was constructed in Takaoka, Toyama with tubes installed beside the building at a buried depth of approximately 2 m. A measurement survey of subterranean heat use was conducted over a 1-year period, fiscal years 2013, and the results are reported herein. The objective of the study was to clarify from measurements the effectiveness of fresh air load reduction obtained through the use of an earth tube system at a buried depth of 2 m by understanding the relationships among outside air temperature and indoor outlet temperature according to the season, and by presenting analysis results focusing on winter heat gain and summer heat extraction, including the latent heat portion.

The features of this study are as follows: (1) an earth tube system (total length approximately 125 m) is installed beside a house at a depth of 2 m to reduce excavation costs; (2) measurements are taken under the condition of a ventilation rate of 0.33 times/h (ventilation air volume, approximately 260 m^3/h), which represents a fresh air load reduction and (3) the sensible and latent heat of the heat extraction in summer and the heat addition in winter under Hokuriku climate conditions in Japan are analyzed.

2. OVERVIEW OF MEASUREMENTS

2.1 HOUSE AND EARTH TUBE SYSTEM

An overview of the house and the earth tube system for which measurements were taken is given in Table 1. Also, Fig. 1 shows the arrangement of tubes buried besides the building. The total floor area of the house is 237 m^2, and the air volume is 790 m^3. The value of a coefficient of heat loss based on Japanese Act on the Rational Use of Energy is 3.79 W/(m^2·K). The northwest of the community house is a park, and the earth tube is laid in the site. Seven vinyl chloride (VU) tubes with diameter ø200 and length 15 m were arranged in parallel and connected to headers of diameter ø300. The total length of subterranean tubing was approximately 125 m (the underground passage distance of the branched air was approximately 35 m). Piping is a comb-like arrangement, and the arrangement interval is 1500 mm. The tubes were laid at a gradient of 1.0%, and a small pump was installed in a shallow sump in the east corner to form a system that draws up condensation water produced inside the tubes during summer. The forced draft fan which installed in the house is BFS-100SSU by Mitsubishi Electric Corp.

2.2 DETAILS OF MEASUREMENT SURVEY

The forced draft fan which installed in the community house is BFS-100SSU by Mitsubishi Electric Corp. and was continuously operated regardless of a season and day and night through the survey period. The diffused air volume was approximately 260 m^3/h with flow rate measuring instrument (KNS-300, Kona Sapporo Corporation, Sapporo, Japan). Since the air volume of the community house is 790 m^3, the ventilation rate is 0.33 times/h.

The measurements taken included the outside air temperature/humidity and the outlet temperature/humidity using a thermo-hygrometer with memory (at 30-minute intervals; TD-72U, T&D Corporation, Nagano, Japan). The site was visited and measurement data were collected approximately once every 4 to 6 weeks.

Table 1: Overview of Takaoka earth tube community house

Over view of house	Location	Takaoka City,Toyama Prefecture	
	Tootal floor area	237m^2	
	Structure	Two-story wooden building	
	Month and year completed	May 2013	
Over view of tube		Header / Branch tube	
	Material	Rigid vinyl chloride	
	Tootal length	Approx. 125m	
	Arrangement interval	1500mm	
	Air volume	approx.260m^3/h	
	Nominal diameter	300 φ / 200φ	
	Length	10150 mm / 15000 mm	
	No.of tubes	2 / 7	

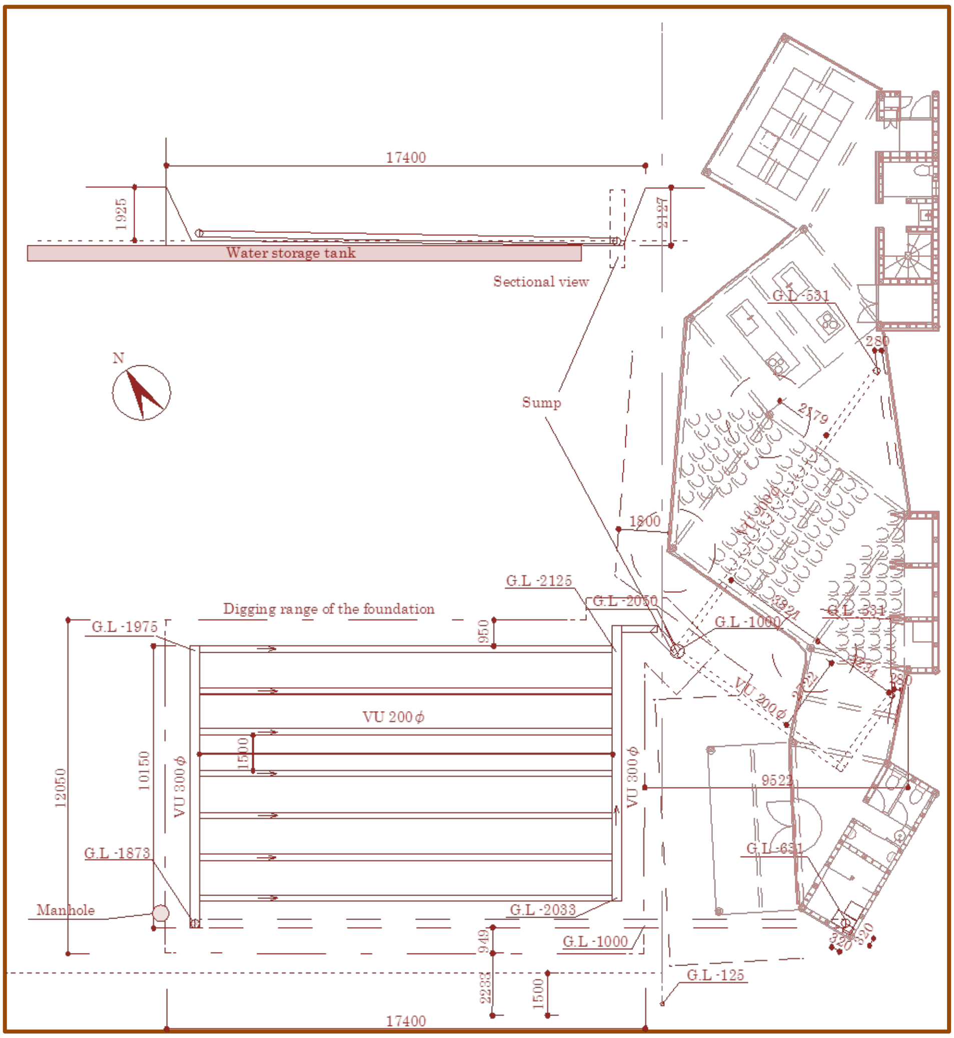

Figure 1: Plan of earth tube community house/tubing diagram and measurement locations.

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3. RESULT AND DISCUSSION

3.1 YEAR-ROUND MEASUREMENT SURVEY OF OUTSIDE AIR, SUBTERRANEAN AND INDOOR OUTLET TEMPERATURES FOR EARTH TUBE SYSTEM

Figure 2 shows the relationship between outside air (tube inlet) temperature/humidity and indoor outlet temperature. It shows the annual variation in daily mean values from May 2013 to April 2014. The monthly mean values for outside air and indoor outlet temperature/humidity are arranged in Table 2 along with a number of valid days used in the calculation.

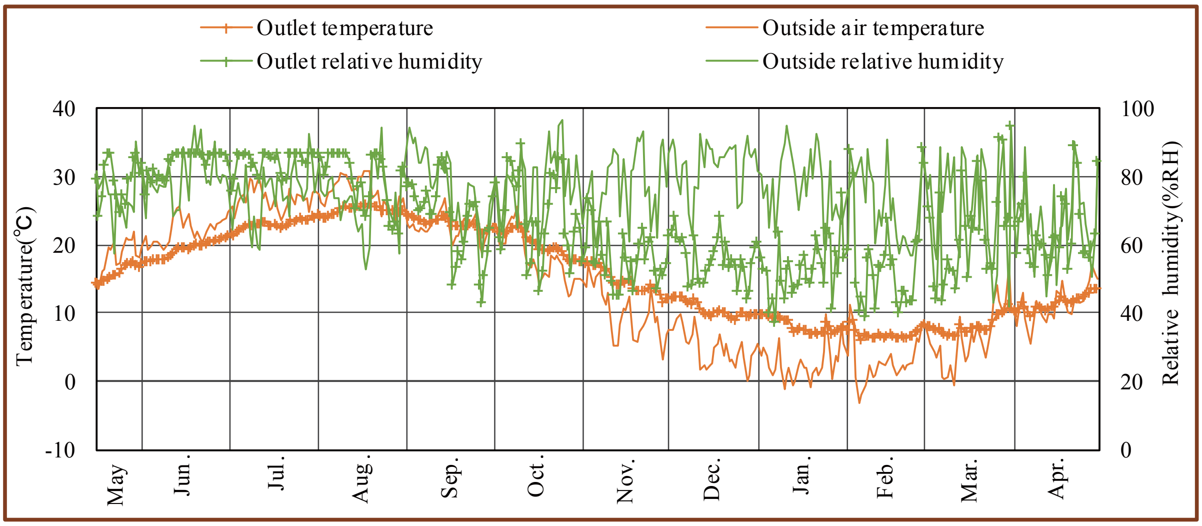

Figure 2: Annual Variation in Daily Mean Values for Outside Temperature/Humidity, Indoor Outlet Temperature/Humidity (May 2013 to April 2014).

Table 2: Monthly Values of Temperature and Relative Humidity.

		2013								2014				Mean, Total
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	
Temperature	Outlet	15.9	19.2	22.9	25.1	23.2	20.3	14.8	10.6	8.2	6.9	8.2	11.5	15.6
	Outside air	18.4	21.9	26.6	27.8	22.6	18.4	10.1	4.9	2.8	3.0	6.5	11.2	14.5
Relative humidity	Outlet	79.1	84.8	84.7	79.7	68.5	70.6	56.8	56.2	53.3	56.1	65.4	64.4	68.3
	Outside air	74.3	80.1	74.6	73.0	78.2	80.0	78.0	84.1	77.6	74.7	72.9	67.7	76.3
No. of valid days		16	30	31	31	30	31	30	31	31	28	31	29	349

Outlet temperature reaches a peak of 25.1 ºC in August, and the lowest value, 6.9 ºC, occurs in February. Outside air temperature peaks in August, 27.8 ºC, and is lowest in January, 2.8 ºC, followed by 3.0 ºC in February. From Figure 2 and Table 2, the period during which the outlet temperature is lower than the outside air temperature and the earth tube system functions as a cooling apparatus is roughly four months, from May through August in Hokuriku. On the other hand, the period during which the outlet temperature is higher than the outside air temperature and the tube system functions as a heating apparatus is approximately 6 months, from October through March.

Looking at the data for monthly mean values of outlet relative humidity, from May to August, this value is high and is in the comparatively low state from November to next year February. When high values are 84.8%RH in June and 84.7% in July, low values are 53.3%RH in January, 56.1%RH in February and 56.2%RH in December etc. Differences in relative humidity between inlet and outlet of the earth tube system originate in heat extraction in summer and heat gain in winter. Particularly in summer months, there are days on which condensation of vapor contained in the air occurs as a result of passing inside the tubes.

Figure 3 shows time- series data of monthly mean values for outlet temperature/humidity and outside air temperature/humidity. Since outside air temperature becomes high in the daytime and low in the nighttime, conversely, the relative humidity of the outside air is high in the nighttime and low in the daytime. The change of outlet air temperature passing the earth tubes becomes small and the difference in temperature through day and night is settled in less than 2 ºC. When seeing about the width of the upper and lower sides of the temperature data plotted, while the difference in outside air temperature is 30 ºC (2-32 ºC), it becomes 19 ºC (7-26 ºC) with outlet temperature. The width of the temperature is reduced to 2/3 by air ventilation using the earth tube system. Also about the relative humidity of outlet air, the change by time becomes smaller.

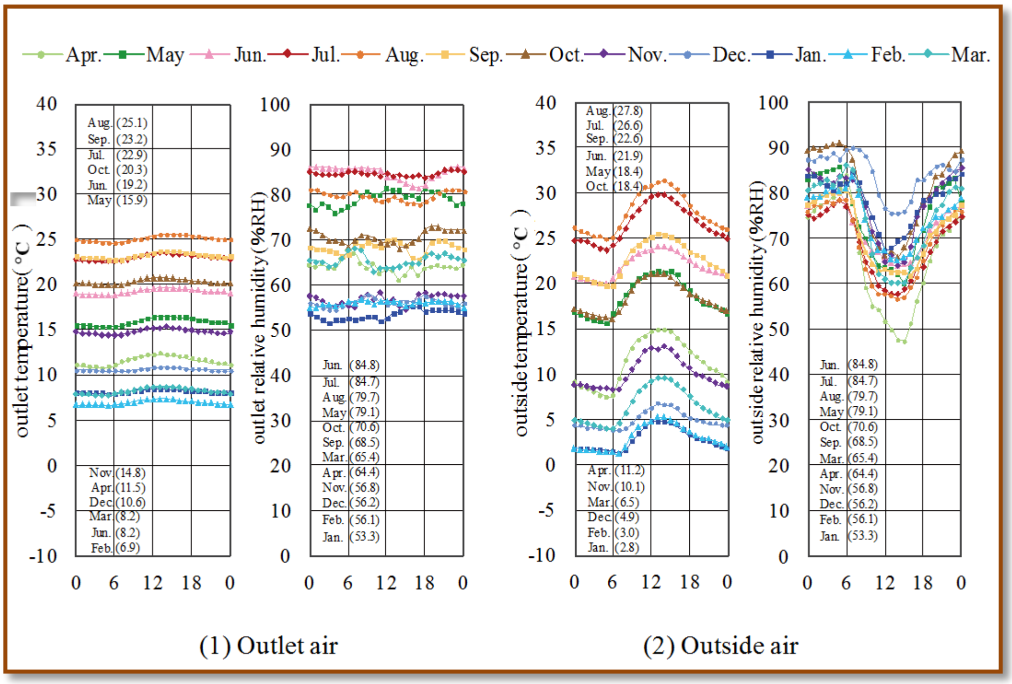

Figure 3: Annual variation in monthly mean values.

The temperature and absolute humidity differences between the outside air and the indoor outlet are fundamental to the calculation of the amount of heat added/extracted by the earth tubes. The rise and fall of outlet temperature and absolute humidity relative to outside air temperature and absolute humidity was calculated for each month, as shown in Fig. 4 and 5. In the figure, the number of time which became a value of plus or a value of minus by monthly, and its average value are shown. The biggest difference between outlet temperature and outside air temperature in

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summer was -3.9 ºC in July, followed by 3.5 ºC in August. The biggest difference in winter was +6.0 ºC in January, followed by +5.8 ºC in December. In terms of sensible heat, it is estimated that the amount of heat added in winter is larger than the amount of heat extracted in summer.

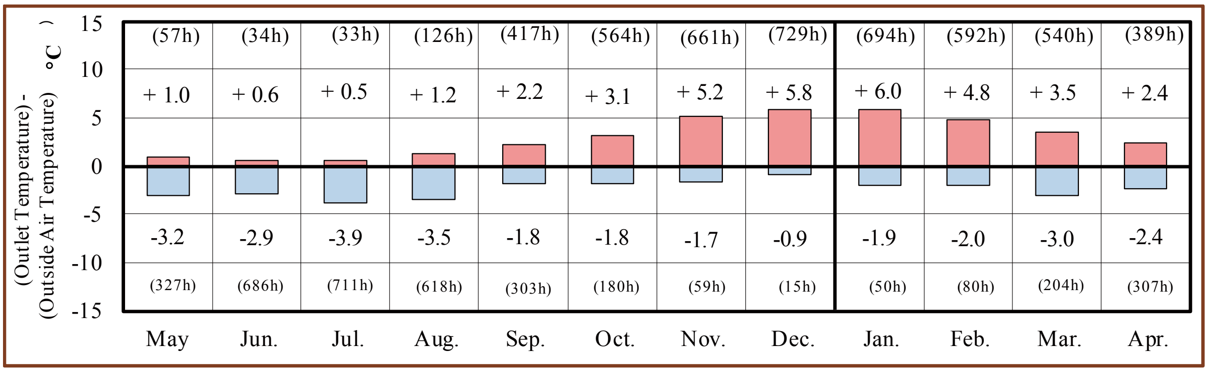

Figure 4: Annual variation in monthly mean values for (outlet temperature) – (outside air temperature).

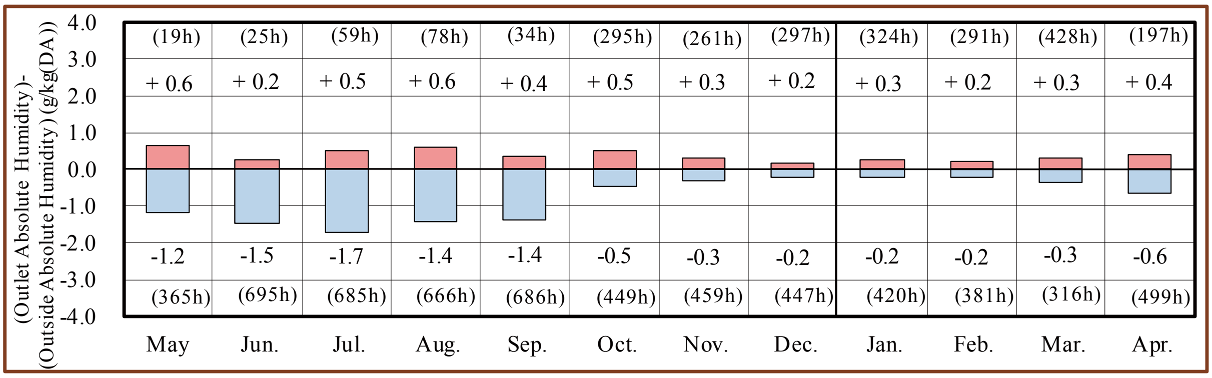

Figure 5: Annual variation in monthly mean values for (outlet absolute humidity) – (outside air absolute humidity).

To the next, looking at the absolute humidity difference, the biggest value in summer was -1.7 g/kg(DA) in July. The difference has become -1.0 g/kg(DA) or more from May to September, and latent heat removal by the earth tube system is expected in this period.

The scatter diagram in Figure 6 shows the seasonal characteristics of the relationship between outside air temperature and indoor outlet temperature. After plotting the daily mean values of outlet temperature versus outside air temperature, simple linear regression was used to obtain the relationship represented by the following equation:

$$y = 0.65x + 6.20 \ (^{\circ}C) \qquad (1),$$

The correlation coefficient in this case is high, at 0.95, and looking at the data by season, it is clear that it transitions in a counterclockwise elliptical manner. During spring (April/May, ○) and fall (October/November, △), when the outside air temperature is around 15ºC, temperatures are below and above the regression line, respectively. In other words, indoor outlet temperatures are distributed below the regression line in spring, because subterranean temperatures are low, and above the regression line in fall, because subterranean temperatures are high. Moreover, this figure shows that outlet temperatures are in the tendency which will be around 25-26 ºC in the time of summer outside air temperature being 30 ºC and will be around 6-7 ºC in the time of winter outside temperature being 0 ºC.

3.2 ANALYSIS OF AMOUNT OF HEAT EXTRACTION/ADDITION BY EARTH TUBE SYSTEM

Figure 7 shows the results of calculation of the daily heat extraction and heat addition amounts at an air exchange rate of 0.33 times/h via the earth tube system. The results are based on the difference in temperature and humidity between the outside air and the indoor outlet measured at 30-minute intervals. Heat gain is shown as a positive value and heat extraction as a negative value; the dark orange indicates sensible heat and the light orange indicates latent heat.

This latent heat portion was evaluated as extracted heat when the absolute humidity of air passing through the tubes decreased and as gained heat when it increased. Details of the calculation of the amount of latent heat are given in the Appendix.

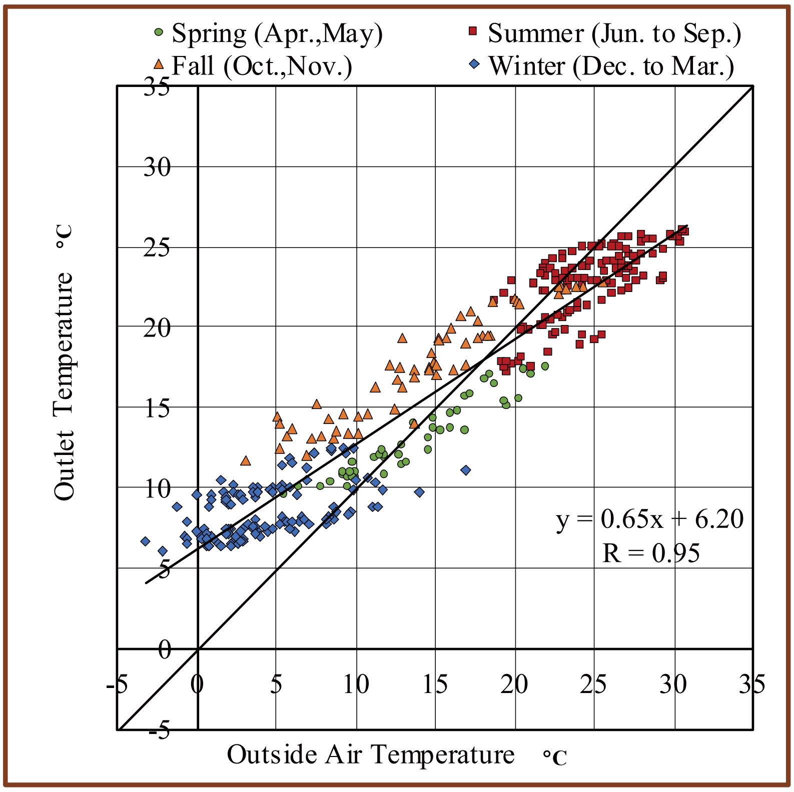

Figure 6: Relationship between outside air temperature and earth tube system outlet temperature.

Looking at the entire year-long period, the trend is mainly heat extraction from May to September and mainly heat gain from mid-October to mid-March. The reason for the days with high values of heat extraction in the end of March 2014 is that outside air temperature rose, which is very unusual for that time of year. Latent heat extraction, which occurs when outside air with high temperature and humidity enters the earth tube system, occurs during the period May to September,

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and days with high latent heat extraction values can be found in June and July. During this period, there are also days on which latent heat gain due to evaporation of condensation water inside the tubes occurs, but compared to the overall amounts over the year, latent heat extraction is greater. The maximums of heat extraction in summer are approximately 85 MJ/day, and the maximums of heat gain in winter are about 75 MJ/day. The latent heat portion has exceeded the sensible heat portion from May to September. Condensation water produced inside the earth tubes during summer draws up at a sump.

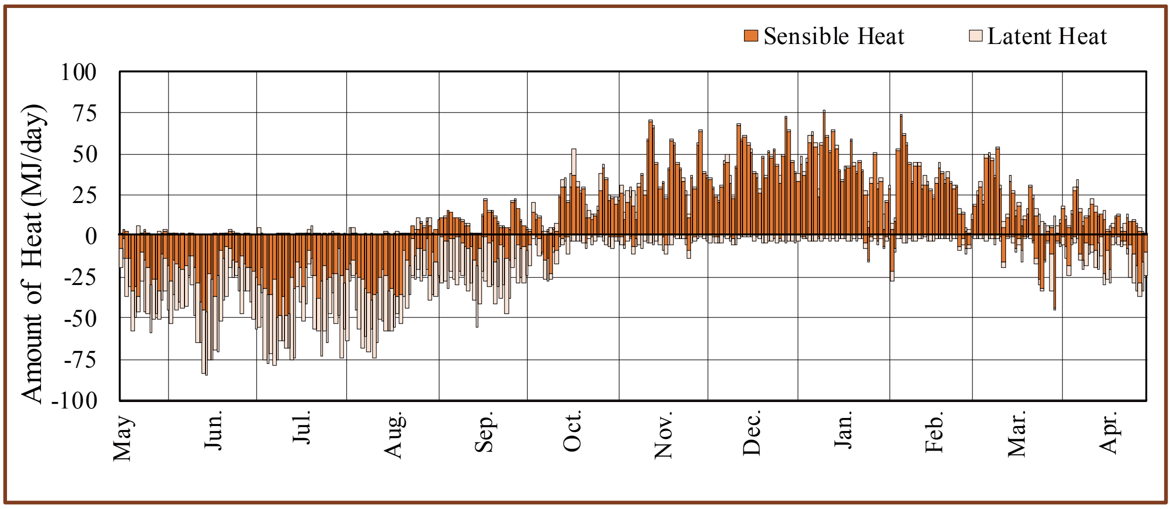

Figure 7: Amount of heat extraction/gain by earth tube system.

(MJ/year)

Heat gain	May to Apr.			Dec. to Mar.		
	+598 / +6390		+6988	+331 / +5160		+5491
Heat extruction	May to Apr.			Dec. to Mar.		
	−3606 / −4638		−8244	−2336 / −3200		−5536

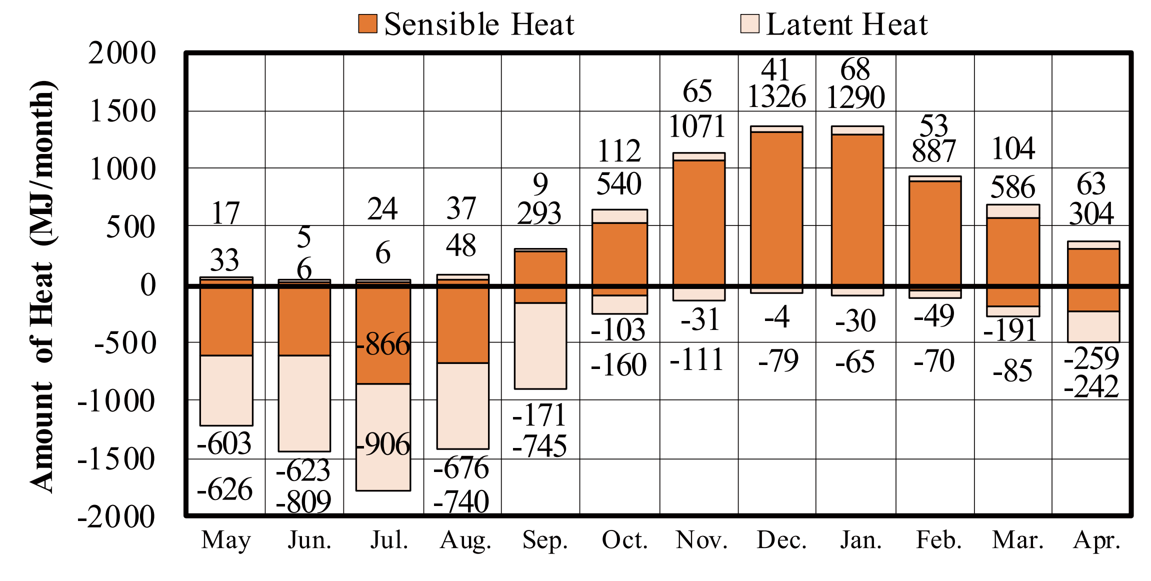

Figure 8: Monthly mean heat extraction/gain by earth tube system.

Figure 8 shows amounts of heat extraction/gain by the earth tube system by the month. When calculating the numeric values categorized by the month in this paper, the daily mean values for the pertinent month were determined using the valid data from a 1-year period, and then multiplied by the number of months and days. From the figure, the peak in heat extraction was in July and, adding together the sensible heat portion of -866 MJ/month and the latent heat portion of -906 MJ/month, it amounted to −1772 MJ/month. Heat extraction in June was approximately 81% of that in July at -1432 MJ/month (sensible heat portion: -623 MJ/month, latent heat portion: -809 MJ/month) and in August was approximately 80% of that in July at -1416 MJ/month (sensible heat portion: -676 MJ/month, latent heat portion: -740 MJ/month). The peak in heat gain was in December and amounted to +1326 MJ/month of sensible heat. However, January had a heat gain approximately 97% of that in December at 1290 MJ/month of sensible heat.

Totals for the year were as follows: The sensible heat portion of heat extraction was -3606 MJ/year and the latent heat portion of heat extraction was -4638 MJ/year, giving a subtotal of -8244 MJ/year. The sensible heat portion of heat gain was +6390 MJ/year and the latent heat portion of heat gain was +598 MJ/year, giving a subtotal of +6988 MJ/year; these results apply when the earth tube system is operated continuously throughout the year.

In the Hokuriku Region, the period during which heat extraction can be expected is from June to September, and heat gain can be expected from November to March. Summing heat extraction and heat gain for each of these periods, the amount of heat extraction is found to be -5536 MJ/year over 4 months, and the amount of heat gain is found to be +5491 MJ/year over 5 months.

As shown in Fig. 4, comparing only the earth tube system outlet temperature and the outside air temperature leads to the conclusion that the effectiveness of using subterranean heat is greater in winter. However, by including enthalpy of latent heat extraction in the evaluation, it was shown that the effectiveness of the earth tube system is actually greater in the summer in the Hokuriku region.

4. CONCLUSION

This paper examined the effectiveness of using subterranean heat in the community house in the Hokuriku region by conducting a year-round measurement survey of outside air and indoor outlet temperature and humidity for an earth tube house constructed in Takaoka, Toyama and calculating heat extraction in summer and heat gain in winter.

The research results are summarized below:

1) Using an earth tube system with a buried depth of 2 m, the total length of tubing, approximately 125 m and ventilation was carried out at an air exchange rate of 0.33 times/h. It was clarified that the monthly mean indoor outlet temperature could be maintained at around 3 to 4 ºC lower than the outside air temperature in summer and around 5 to 6 ºC higher than the outside air temperature during winter. The biggest difference between outlet temperature and outside air temperature in summer was -3.9 ºC in July, and the biggest difference in winter was +6.0 ºC in January. The fall of the absolute humidity of outlet air in comparison with outside air was remarkable in May to September, and the values were -1.2 g/kg(DA) to -1.7 g/kg(DA).

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2) The peak in heat extraction by the earth tube system was -1722 MJ/month in July and the latent heat portion of -906 MJ/month has exceeded the sensible heat portion of -866 MJ/month. The peak in heat gain was +1367 MJ/month in December. In the heat acquisition which occurs in winter, there is the feature that the amount of sensible heat occupies most among the total heat, such as approximately 97% in December. Moreover, when evaluated including latent heat removal, it becomes clear that the thermal effect of an earth tube system in summer is larger than in winter, even in north latitude 36-degree Takaoka City.

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6. APPENDIX

The following formulae were used to calculate latent heat gain/extraction (Inoue 2008):

$h = h_a + x \cdot h_v$ (A.1)

$h_a = 1.006 \cdot t$ (A.2)

$h_v = 2501 + 1.805t$ (A.3)

$x = 0.622p_v/(P - p_v)$ (A.4)

$p_v = \varphi \cdot p_s/100$ (A.5)

$p_s = 133.3\exp(18.808t + 361.52/t + 237.54)$ (A.6)

Here,

h: Specific enthalpy [kJ/kg']

h_a: Specific enthalpy of dry air [kJ/kg']

x: Absolute humidity [kg]

h_v: Specific enthalpy of water vapor [kJ/kg]

t: Temperature [ºC]

p_v: Partial pressure of water vapor [kPa]

P: Standard atmospheric pressure, 101.325 [kPa]

ϕ : Relative humidity [%]

p_s: Saturated water vapor pressure [Pa]

Results based on the above formulae are multiplied by the house's ventilation air volume (260 m^3/h) at 0.33 times/h.

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