A Field Measurement of the Utilizing Geothermal and External Insulated House in Winter Season with Energy and Exergy Analysis

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Abstract
*The house standing in Otaru City, Hokkaido, has built with an external insulation and a Ground Source Heat Pump (GSHP), and we measured the indoor thermal environment and the use of electric power into the GSHP in winter season. Based upon the results of the measurement, energy and exergy flows from underground soil to the outdoor air via the GSHP, the indoor air and building envelopes were numerically analyzed. First, the indoor air temperature has been kept from 18 to 21℃. Second, the heat loss coefficient of the measurement has been 1.0W/m^2*K. Third, the GSHP has efficiently operated with the average System Coefficient of Performance (SCOP) of 4.5. Fourth, in the lowest daily mean outdoor air temperature (-9.3℃), the GSHP consumed 30% of input thermal exergy of underground soil and electric exergy, so that supplied 70% of thermal exergy into the indoor air. Finally, we analyzed and simulated three cases of the exergy consumption processes from the power plant to the outdoor air through the GSHP, the indoor air and building envelopes. As a consequence, in the lowest daily mean outdoor air temperature, to keep the mean indoor air temperature at 19.6℃, 60% of exergy was consumed between the power plant and the GSHP, and the rest, 40% of exergy was consumed inside the GSHP, the indoor air and building envelopes.*

Keywords – GSHP, External Insulation, SCOP, Exergy Consumption

1. INTRODUCTION

In recent, Ground Source Heat Pump (GSHP) systems widely spread mainly in European countries and Northern America because systems use an efficient renewable energy. More than 1.1 million GSHP units have been installed in worldwide [1]. Moreover, installations of GSHP systems are rapidly increasing over the past decade. Various researches about GSHP systems have been done as much as increasing GSHP installations. These researches have revealed that the systems provide higher efficiency and less electrical energy demand than conventional heating, ventilation and air-conditioning (HVAC) systems [1-3], and even more researches are continuing all over the world.

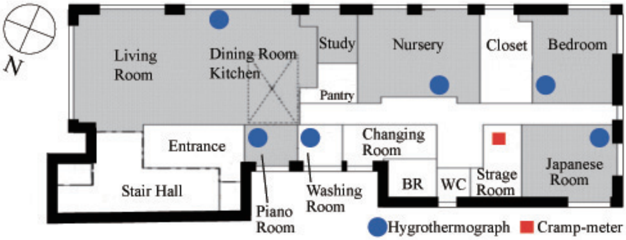
In Japan, GSHP units rapidly spread in the past few years, and approximately 1000 units have been installed so far. 56% of the total units are installed in commercial building such as schools, hospitals and public buildings, and 44% of units are installed in residential buildings. In addition, 84% of the total units are installed with vertical closed-loop systems [4]. Hokkaido, where is the northern island of Japan, has installed 33% of total units. Hokkaido is the coldest prefectures in Japan; average annual temperature is 8.9°C (Tokyo-16.3°C, Okinawa–23.1°C) and climate conditions are similar to northern European cities and Canadian cities [5]. In Hokkaido, high efficient northern regional houses, "*Hoppo-Gata* houses," have recently developed [6]. For conserving more energy uses, some of these houses are built with external insulation and install GSHP systems. However, the initial cost for installing and operating GSHP systems are still more expensive than conventional HVAC systems; therefore, buildings installing the GSHP systems are still minor cases. Because Japan is standing behind to introduce GSHP systems, more researches and data of GSHP systems are necessary to establish the systems in Japan.

Prior researches have more likely revealed the efficiency of GSHP systems in different conditions, environmental impacts, cost performances of installing, and operating and maintenance [7-11]. These researches have evaluated systems by energy-based theories. Because energy explains a concept of the conservation, energy itself is never consumed, whereas it can be transformed the other form. On the other hand, exergy can be expressed as a concept of quality of energy and derived by the first law and the second law of thermodynamics. Exergy is also a concept that quantitatively expresses the consumption. Energy consumption, that we usually call, actually expresses the energy input into systems. In other words, energy can be discussed by the amount of inputs. On the other hand, exergy can describe the supply and the consumption. Approaching by the exergy concept, which is considering the supply and the consumption, can "theoretically" explain how resources will be performed within thermodynamic flows [12]. However, researches approached by exergy concepts are still few comparing with prior researches [13]. Therefore, the concept of exergy is an approach and a measuring tool to analyze a thermal environment of buildings and to design efficient thermal systems as a new insight [12-14].

In this measurement, we analyzed an indoor thermal environment, the SCOP of the GSHP in combination with closed-loop system, and energy and exergy flows from the underground soil to the outdoor air in winter season.

2. MEASUREMENT METHOD

The building (the total floor area of 842m^2) has built in Otaru, Hokkaido where is locating in northwest of Sapporo and has much snow at the average outdoor air temperature of -3.0°C in winter season. This building is a four floors building and has been constructed with reinforced concrete, and its envelopes are constructed with the external insulation. The 1st and 2nd floors are used as a clinic and 3rd and 4th floors are used as residential spaces. In front of the building, there are large openings of the triple Low-E glazing (U-value of 1.33W/m^2*K). A GSHP system (with a closed-loop system) with the rated power of 10kW operates the hot-water floor heating and panel heating. The heat loss coefficient of the planning is 1.3W/m^2*K without the sensible heat exchanger. On the other hand, the coefficient becomes 1.0W/m^2*K with its heat exchanger (effectiveness of 72%).



Picture 1. An appearance of the building from northeast

We measured the indoor thermal environment and the amount of input electric power into the GSHP system on the 3rd floor (the floor area of 232m^2) from December 14th, 2011 to April 26th, 2012. In addition, supplying and returning temperature of a refrigerant on the source side and supplying and returning temperature of hot water on the distribution side were measured in the machine room on the 2nd floor. The detail of locations of measuring instruments on the 3rd floor is shown in Figure 1. From collected data, the heat loss coefficient by measured values, the SCOP of the GSHP system, and energy and exergy flows were numerically analyzed.

3. RESULTS

3.1 Thermal Environment

Figure 2 shows the outdoor air temperature and each room air temperature of two weeks when the outdoor air temperature drastically decreases from 2 to -12°C. Even though the outdoor air temperature decreases, each room air temperature keeps between 18 and 21°C, and differences of each indoor air temperatures within 24 hours are within 2 to 3°C. The globe temperature is similar to the indoor air temperature. Therefore, it can be considered that building envelopes including openings effectively insulate against the outdoor environment.

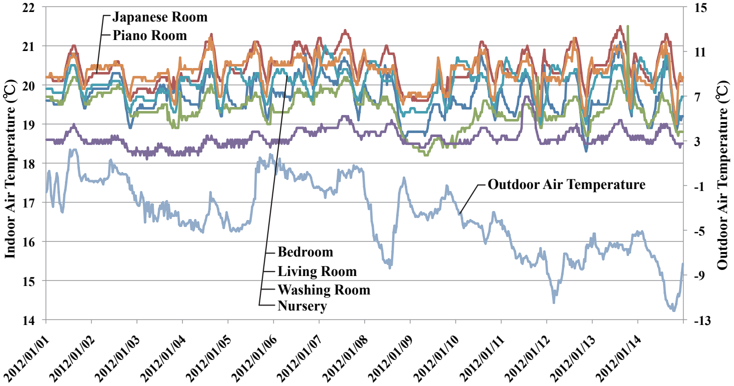


Figure 2. The outdoor air temperature and indoor air temperatures of each room on Jan. 1st – 14th, 2012

Figure 3 shows supplying and returning temperatures of the refrigerant on the source side and of hot water on the distribution sides of the GSHP.

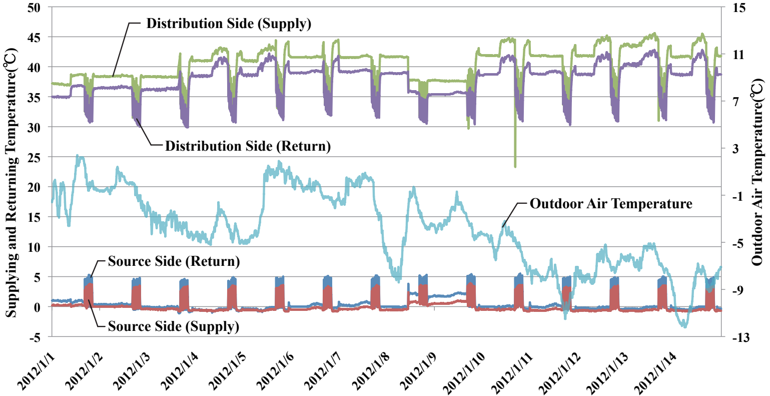


Figure 3. Supplying and returning temperatures of refrigerant and hot water on the source and the distribution sides, respectively

When the GSHP is operated, the returning temperature on the source side keeps at 5°C, although the outdoor air temperature gradually decreases. On the other hand, the supplying temperature of hot water on the distribution side increases. On Jan. 1st and 2nd, the supplying temperature of hot water is at 39°C against the outdoor air temperature around 0°C, however, on Jan. 14th, the supplying temperature of hot water increases to 45°C when the outdoor air temperature reaches to -12°C.

Figure 4 shows the input electric power of the two weeks. The GSHP is stably operated by the input electric power of 1900W from afternoon to dawn of next morning. Although the supplying temperature of hot water on the distribution side increases from 39°C to 45°C, the maximum input electric power into the GSHP stably keeps around 1900W. This tendency is kept during the whole measuring period.

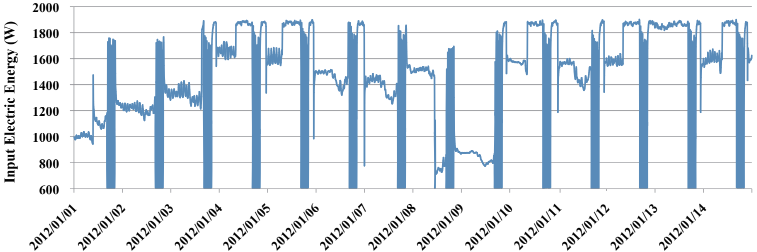


Figure 4. Input electric energy into the GSHP

3.2 The Heat Loss Coefficient

A relationship between differences of daily means of indoor - outdoor temperature and daily means of the amount of input energy into the residential space is shown in Figure 5. By a gradient of the regression line, the heat loss coefficient of the measurement can be expressed as 1.0W/m2*K. In addition, the natural indoor – outdoor temperature difference calculated by X-intercept is 7.8°C. The heat loss coefficient of the planning is 1.0W/m2*K

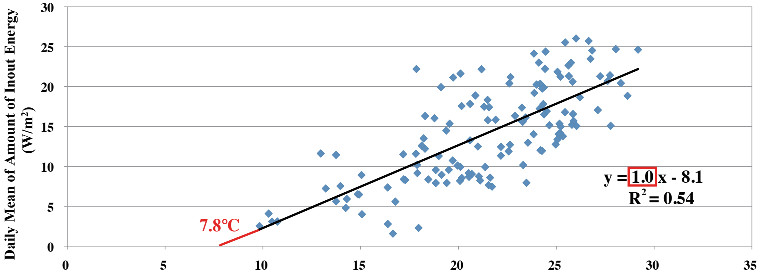
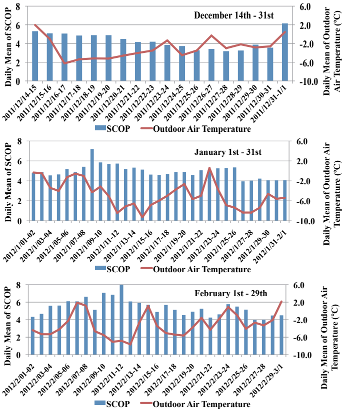


Figure 5. Daily means of the indoor-outdoor temperature differences and the amount of input energy into the residential space

with the sensible heat exchanger; therefore, the heat loss coefficient from the data of measurement on the 3rd floor expresses the same efficiency of the thermal insulation as the planning.

3.3 SCOP of the GSHP

As shown in Figure 6, daily means of SCOP that is calculated by the amount of input energy into the residential space and the input electric power between 6pm and 6am gradually increases from December to February; on the other hand, daily means of the outdoor air temperature decrease. Figure 7 shows monthly means of SCOP and monthly means of the outdoor air temperature. The reason of increasing the SCOP is considered that warmer geothermal energy (exergy) is efficiently supplied into the source side of the GSHP when operated by 1900W.



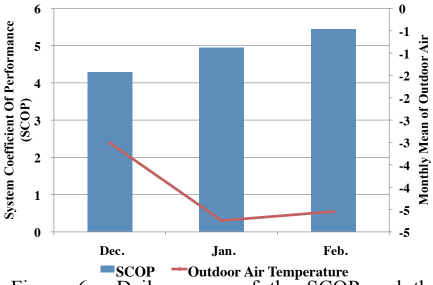


Figure 6. Daily means of the SCOP and the outdoor air temperature, Dec.-Feb. (Left)

Figure 7. Monthly means of the SCOP and the outdoor air temperature, Dec.- Feb. (Above)

3.4 Energy and Exergy Flows

Energy and exergy flows from the underground soil to the outdoor air on Jan. 14th, 2012, when the daily mean of the outdoor air temperature is the lowest, are shown in Figure 8 and 9. Respective values of the inside arrow express the daily mean of energy and exergy flows.

In the energy flow, as shown in Figure 8, the geothermal energy from a refrigerant of 4006W (i) and the electric energy of 1000W (ii) are supplied into the GSHP, and the total energy of 5006W (iii) is transferred to the distribution side. As a result, the temperature of hot water increases, and the energy of 5006W is supplied into the room. In addition, thermal energy of 1121W (iv) from solar radiation, occupants, lightings and other electronics is also added to the energy of 5006W. The total energy of 6127W (v) goes into building envelopes through the room air. Finally, the total energy of 6127W (vi) comes out to the outdoor air. The average SCOP of the GSHP on the day is 5.0 (= 5006W/1000W). In this energy flow, geothermal energy carried by a refrigerant is transferred to hot water, transformed to room air, and finally

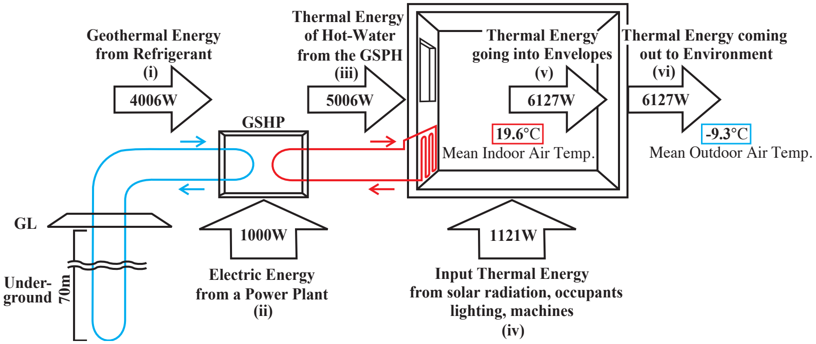


Figure 8. The energy flow on Jan. 14th, 2012

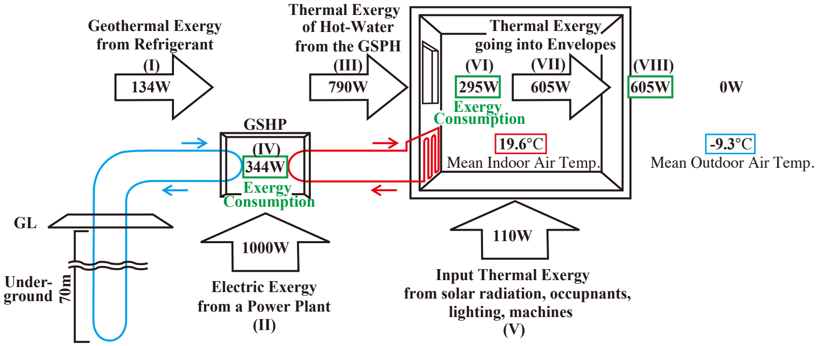


Figure 9. The exergy flow on Jan. 14th, 2012

released to the outdoor. Also, this flow rationally expresses conservations of energy.

On the other hand, the exergy flow can explain “consumption” at each system, as shown in Figure 9. The geothermal exergy of 134W transferred by the refrigerant (I) and electric exergy of 1000W (II) are supplied into the GSHP. Electric exergy is equivalent to electric energy (Electric exergy = Electric energy). The hot water heated up in the GSHP has the thermal exergy of 790W, and the thermal exergy is supplied into the indoor air (III). A difference between the exergy of 1134W (= 134W + 1000W) and 790W expresses the exergy consumption, 344W (IV), at inside of the GSHP (1134W – 790W = 344W). Then, the thermal exergy of 900W are supplied from hot water (III) and other input exergies (V). To keep indoor air temperature at 19.6℃, 295W exergy is consumed in the indoor air (VI). The rest of thermal exergy of 605W goes into building envelopes (VII). Finally, the rest of all thermal exergy is consumed at the inside of building envelopes (VIII); thus, the exergy in the outdoor air becomes 0W. In this flow, it is considered that exergy is supplied and consumed at each system to keep the daily mean indoor air temperature at 19.6°C against the outdoor air temperature at -9.3°C.

3.5 Exergy Consuming Processes

The exergy theory can explain consumptions of each system for whole space heating; therefore, processes of exergy consumption from a power plant to the outdoor air of a building via heating facilities, the indoor air, and building envelopes can be calculated. Figure 10 and 11 show the processes of exergy consumption, and simulated processes with different heat loss coefficient, based on Jan. 14th, 2012.

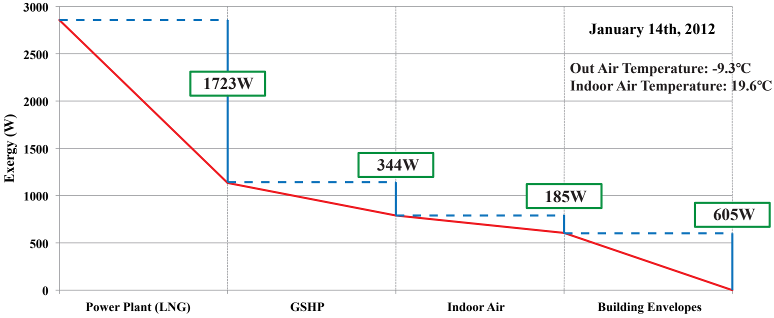


Figure 10. The process of exergy consumption in each system on Jan. 14th, 2012

In Figure 10, the line shows the process of exergy consumption and each value shows the amount of exergy consumptions in systems. In this calculation, we assumed the thermal energy efficient of the power plant, that is exactly equal to the ratio of exergy produced as electricity to the higher heating value of LNG supplied, is 0.35 [11]. As a result, 60% (1723W) of exergy, which is supplied into the power plant, is consumed before reaching to the GSHP, 12% (344W) is consumed in the GSHP, 7% (185W) is consumed in the indoor air, and 21% (605W) is consumed in building envelopes. Therefore, the rate of exergy required at the power plant to operate the GSHP system is 2857W.

The processes of exergy consumption are simulated and compared with different heat loss coefficients of 1.0 (measured value) versus 1.5 and 2.0W/m2*K, as shown in Figure 11. We assumed that only building envelopes are different with the condition of the measurement; thus, SCOP of the GSHP and the indoor air temperature are exactly same as the measurement on Jan. 14th, 2012. In Case 1, nearly twice amount of exergy (4837W) is required at the power plant to make the daily mean indoor air temperature keep at 19.6°C. On the other hand, in Case 2, it requires less amount of exergy (4005W) at the power plant than Case 1, but still requires larger amount of exergy than the measurement.

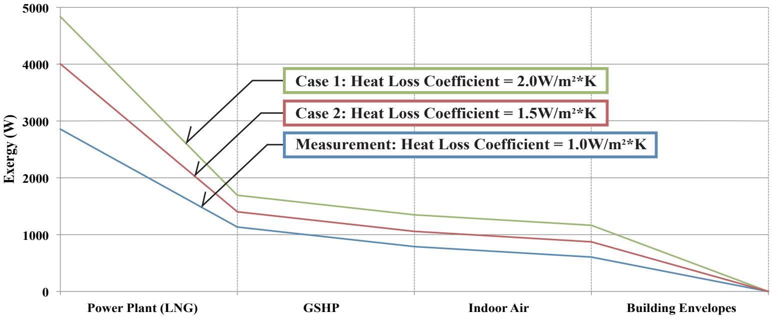


Figure 11. A Case Study of the processes of exergy consumption at each system with Case 1: heat loss coefficient of 2.0W/m^2*K and Case 2: that of 1.5W/m^2*K against the measurement; that of 1.0 W/m^2*K

This simulation shows how building envelopes efficiently influence to exergy requirement at the power plant. Planning building envelopes is an important approach to reduce exergy demand at a power plant, and choosing higher efficient equipments could also reduce more exergy demand for a building. Therefore, it is important to consider architectural environments with exergy flows and to design exergy consumptions at each system.

4. CONCLUTION

In this field measurement, the indoor thermal environment, heat loss coefficient of measurement, the SCOP of the GSHP are measured. Energy and exergy flows were numerically analyzed, and processes of exergy consumption were simulated. The conclusion is as follows;

1. Each indoor air temperature during the measurement kept at 18 to 21°C, and the globe temperature was similar temperature to indoor air temperature.
2. The heat loss coefficient by the planning of 1.0W/m^2*K and the heat loss coefficient by the measurement of 1.0W/m^2*K are the same, therefore, the building has the high efficiency of thermal insulation as much as the planning.
3. Because of stable ground temperature and high insulation, the average SCOP was 4.5 during the field measurement.
4. In the lowest outdoor air temperature during the measurement, the GSHP consumed 30% of the input exergy, which was supplied from the underground and the power plant, and supplied 70% of thermal exergy into the indoor air.
5. Differences of building envelope change exergy consumptions at whole space heating system; therefore, decreasing heat loss coefficient, less

exergy is required at the power plant to make the indoor air temperature keep at a certain temperature for thermal comfort.

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