12th IEA Heat Pump Conference 2017

Development of Simulation Tool for the Shallow Ground Source Heat Pump System Using Vertical Spiral Ground Heat Exchangers and Its Application

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Abstract

The authors developed a simulation tool for the shallow ground source heat pump（GSHP) system using vertical spiral ground heat exchangers (VSGHEXs). In the simulation tool, the temperature variation caused by ground surface is superposed for the ground temperature calculation. The capacity resistance model is applied in order to consider the capacity of inside VSGHEX. In this paper, the outlines of the simulation tool are explained. Next, the simulation tool was validated by comparing with the value measured in the field experiment using the VSGHEXs. Additionally, the authors assumed that the shallow GSHP system using VSGHEXs is installed in the residential house and carried out the feasibility study. The number of VSGHEXs that can operate the shallow GSHP system over the long term was investigated in response to the residential house's insulation performance and the region. Lifecycle cost (LCC) of the shallow GSHP system was calculated and compared to the conventional air source heat pump system.

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"Keywords: Ground Source Heat Pump System, Vertical Spiral Ground Heat Exchager, Simulation Tool;"

1. Introduction

The GSHP system using VSGHEXs has the potential to reduce the installation cost of the GSHP system in Japan. The reason is that the boring machine that is commonly used to build the electrical pole can be utilized.

Additionally, the spiral pipe for the VSGHEXs can be commercial available. On the other hand, the VSGHEXs are buried the shallow layer with the depth of less than 20 m and the borehole diameter of 300~800 mm is much larger than the one of conventional borehole GHEXs. Therefore, it is required to consider the ground surface effect and the heat capacity of inside VSGHEX when the GSHP system using VSGHEXs is designed.

The authors developed a simulation tool for the shallow GSHP system using VSGHEXs. In the simulation tool, the temperature variation caused by ground surface is superposed for the ground temperature calculation. The capacity resistance model is applied in order to consider the capacity of inside VSGHEX. In this paper, the outlines of the simulation tool are explained. Next, the simulation tool was validated by comparing with the value measured in the field experiment using the VSGHEXs. Additionally, the authors assumed that the shallow GSHP system using VSGHEXs is installed in the residential house and carried out the feasibility study. The number of VSGHEXs that can operate the shallow GSHP system over the long term was investigated in response to the residential house's insulation performance and the region. Lifecycle cost (LCC) of the shallow GSHP system was calculated and compared to the conventional air source heat pump system.

2. Outlines of simulation tool for shallow GSHP system using vertical spiral ground heat exchangers

2.1 Outlines of simulation tool

The authors developed a simulation tool for the shallow GSHP system using VSGHEXs by combining the capacity resistance model (CaRM) with the superposition of response of cylindrical heat source model. Figure1 shows the calculation flow and Figure2 is the CaRM inside VSGHEX. In the calculation model of VSGHEX, the VSGHEX's specification such as the depth, the total pipe length, the pipe diameter, the spiral diameter, etc., are given. By using CaRM and the superposition, the outlet temperature of VSGHEX is calculated. The CaRM is applied in order to calculate the temperature inside VSGHEX. The superposition of response of cylindrical heat source model is used for calculating the ground temperature surrounding the VSGHEX. In addition, the VSGHEX is generally buried the shallow layer with the depth of less than 20 m. Therefore, the calculation method for the ground temperature considering the influence of ground surface, which was previously introduced, is applied.

Figure 3 is the plane view of VSGHEX. One thermal node is built between pipe1 and pipe2 and other thermal node is set between pipe2 and the borehole surface like shown in Figure3. The grout inside the pipe2 is called as grout(Core) and the grout outside pipe2 is defined as grout(Shell). The heat balance equations at the thermal nodes of the heat carrier fluid in pipe1, the heat carrier fluid in pipe2, the surface of pipe1, the surface of pipe2, grout(Core), and grout(core) can be expressed by the following equations, respectively.

$$m_w c_w (T_{pin} - T_{w1}) - \frac{T_{w1} - T_{p1}}{\frac{1}{2\pi r_{u2} h l p_1} + \frac{1}{2\pi l_{p1} \lambda_p} \ln\left(\frac{r_{u1}}{r_{u2}}\right)} = c_w \rho_w \pi {r_{u2}}^2 l_{p1} \frac{dT_{w1}}{dt} \tag{1}$$

$$m_w c_w (T_{w1} - T_{w2}) - \frac{T_{w2} - T_{p2}}{\frac{1}{2\pi r_{u2} h l_{p2}} + \frac{1}{2\pi l_{p2} \lambda_p} \ln\left(\frac{r_{u1}}{r_{u2}}\right)} = c_w \rho_w \pi {r_{u2}}^2 l_{p2} \frac{dT_{w2}}{dt} \tag{2}$$

$$\frac{T_{w1} - T_{p1}}{\frac{1}{2\pi r_{u2} h l_{p1}} + \frac{1}{2\pi l_{p1} \lambda_p} \ln\left(\frac{r_{u1}}{r_{u2}}\right)} + \frac{T_{core} - T_{p1}}{\frac{1}{2\pi l_{p1} \lambda_{grout}} \ln\left(\frac{r_{core}}{r_{u1}}\right)} = 0 \tag{3}$$

$$\frac{T_{core} - T_{p2}}{\frac{1}{2\pi l_{p2core} \lambda_{grout}} \ln\left(\frac{r_{p2}}{r_{core}}\right)} + \frac{T_{shell} - T_{p2}}{\frac{1}{2\pi l_{p2shell} \lambda_{grout}} \ln\left(\frac{r_{shell}}{r_{p1}}\right)} + \frac{T_{w2} - T_{p2}}{\frac{1}{2\pi r_{u2} h l_{p2}} + \frac{1}{2\pi l_{p2} \lambda_p} \ln\left(\frac{r_{u1}}{r_{u2}}\right)} = 0 \tag{4}$$

$$\frac{T_{p1}-T_{core}}{\frac{1}{2\pi l_{p1}\lambda_{grout}}\ln\left(\frac{r_{core}}{r_{u1}}\right)}+\frac{T_{p2}-T_{core}}{\frac{1}{2\pi l_{p2core}\lambda_{grout}}\ln\left(\frac{r_{p2}}{r_{core}}\right)}=c_{grout}\rho_{grout}l_{p1}\pi\left({r_{p2}}^2-{r_{u1}}^2\right)\frac{dT_{core}}{dt} \quad (5)$$

$$\frac{T_{p2}-T_{shell}}{\frac{1}{2\pi l_{p2shell}\lambda_{grout}}\ln\left(\frac{r_{shell}}{r_{p1}}\right)}+\frac{T_{s}-T_{shell}}{\frac{1}{2\pi l_{p1}\lambda_{grout}}\ln\left(\frac{r_{b}}{r_{shell}}\right)}=c_{grout}\rho_{grout}l_{p1}\pi\left({r_{b}}^2-{r_{p1}}^2\right)\frac{dT_{shell}}{dt} \quad (6)$$

Here, the values l_{p2core} and $l_{p2shell}$ are the representative length to calculate the thermal resistance. The values are calculated by the following equations.

$$l_{p2core}=\frac{l_b A_{p2}}{A_{p2core}} \quad (7) \qquad l_{p2shell}=\frac{l_b A_{p2}}{A_{p2shell}} \quad (8)$$

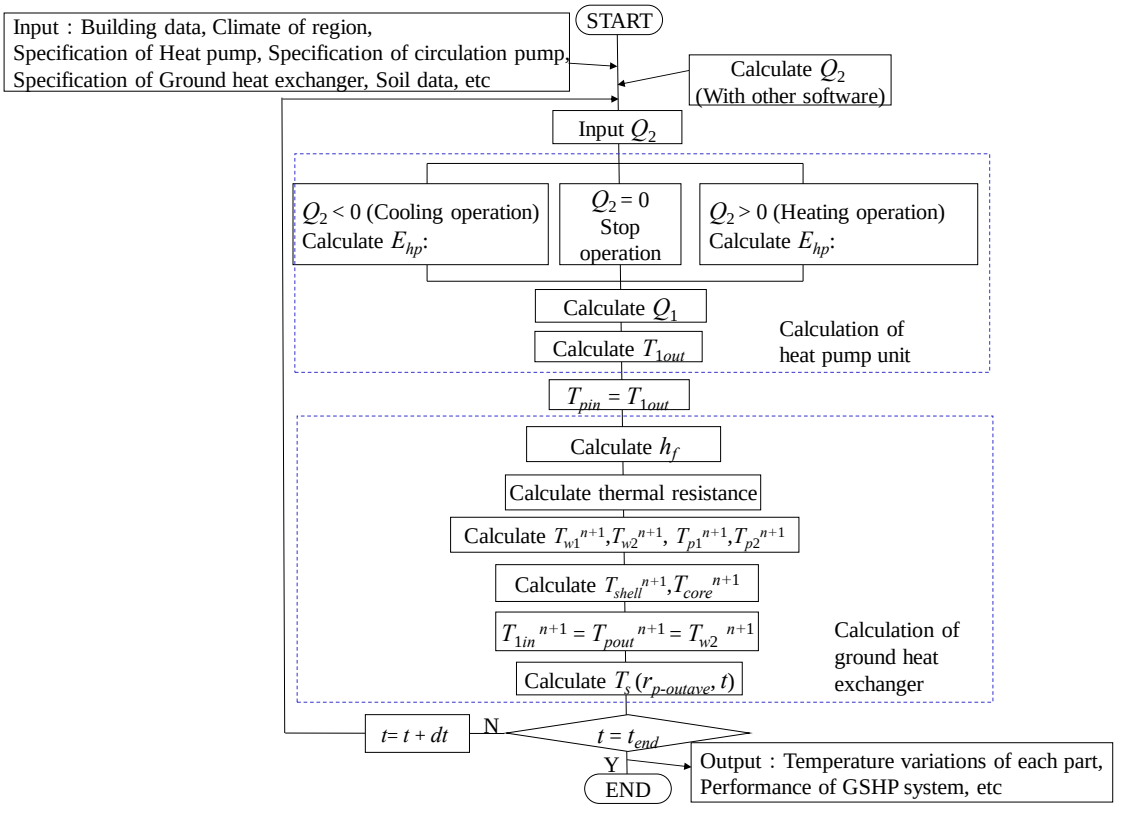


Figure 1Calcualtion flow of simulation tool

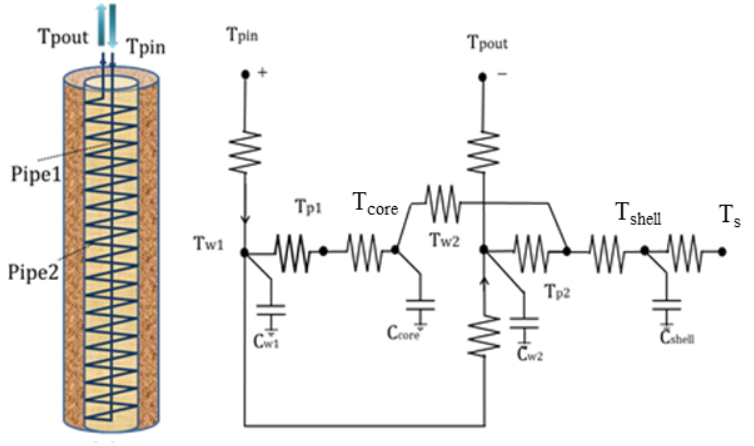


Figure 2 Calculation model of VSGHEX

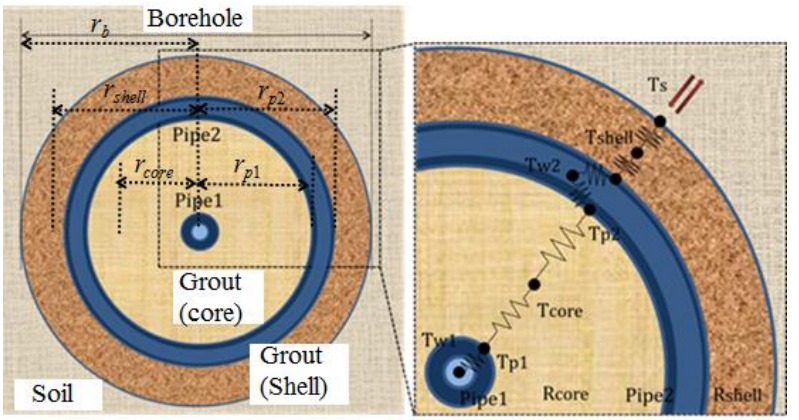


Figure 3 Section view of VSGHEX

2.2 Validation of simulation tool by comparing result of thermal response test

The thermal response test (TRT) shown in Figure4 was carried out in Miyagi Pref. in order to validate the accuracy of the simulation tool. In the TRT, the water has been circulated on the condition of constant flow late (approximately 7 L/min) and constant heating rate (approximately 5 kW) from Oct 20th 2015 to Oct 30th 2015. The VSGHEX with the depth of 4 m was used. The pipe inside and outside diameter are 0.026 m and 0.032 m, respectively. The spiral diameter is 0.6 m and the pipe total length is 75 m. Then the inlet and outlet temperatures of GEHX, underground temperatures and flow rate were measured as shown in Figure4.

Table1 shows the calculated conditions. The effective thermal conductivity is set as 1.3 W/m/K, which was obtained by the TRT previously conducted. Figure5 compares the measured outlet temperature with the one calculated by using the simulation tool. Good agreement with the measured outlet temperature and the calculated one is observed.

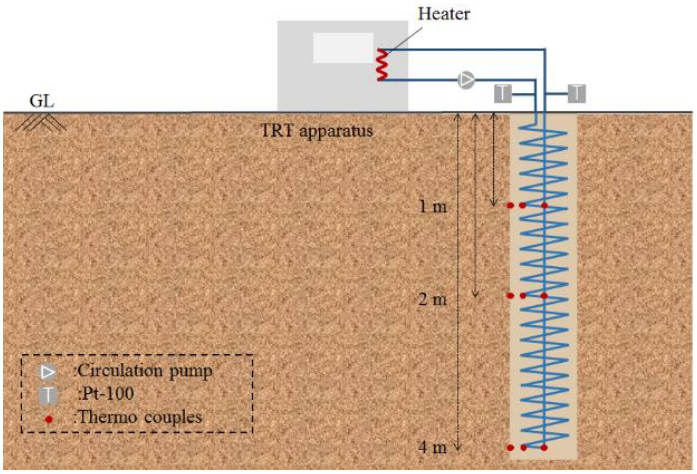


Figure 4 Schematic diagram of TRT

Table 1 Calculated conditions

VSGHEX	Type of GHEX	VSGHEX
	Effective depth of GHEX [m]	4
	Borehole diameter [m]	0.7
	Spiral pipe diameter [m]	0.6
	Pipe outside diameter [m]	0.026
	Pipe inside diameter [m]	0.032
	Pipe thermal conductivity [W/m/K]	0.4
	Grout effective thermal conductivity [W/m/K]	1.3
Ground condition	Effective thermal conductivity [W/m/K]	1.3
	Density [kg/m^3]	1500
	Specific heat [kJ/kg/K]	1.5
	Undisturbed ground temperature [^{o}C]	14.5

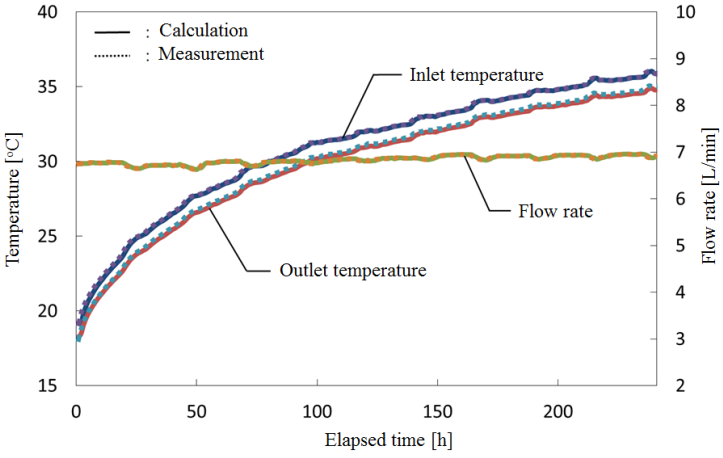


Figure 5 Comparison of temperature variation

3. Investigation of vertical spiral ground heat exchanger's optimum specification by using simulation tool

3.1 Calculated condition

By using simulation tool, the temperature of heat carrier fluid on the condition of constant flow rate and constant heating rate (similar to the TRT) was calculated several times by changing the VSGHEX's such as the spiral diameter, the total length of pipe. Then, the temperature variations were compared and the VSGHEX's optimum specification was investigated. Table 2 shows calculation conditions. The depth of VSGHEX is set at 4 m. The pipe inside and outside diameter are 0.026 m and 0.032 m, respectively. The soil effective thermal conductivity and the grout effective thermal conductivity are given as 1.8 W/m/K. In the first case study, the total length of pipe was fixed at 50 m and the spiral diameter was varied from 0.2 m to 0.7 m at the 0.1 m intervals. In the second case study, the spiral diameter was fixed at 0.6 m and the total length pipe was changed from 50 m to 250 m at the 50 m intervals. In addition, the heating and non-heating interval was changed 24 h(continuous), 12 h(heating)-12 h(non-heating), and 8 h(heating)-16 h(non-heating) in each case study. After the calculation, the performance of VSGHEX was evaluated by adopting the heat injection rate per the VSGHEX's depth and the tmperature difference q'_p. The value q'_p can be calulated by the follwoing equation..

$$q'_p = q_p/(T_{pm} - T_{s0}) = q_p/\Delta T_{pm} \tag{9}$$

Here, q_p is the heat injection rate per VSGHEX's depth. The tempareture T_{pm} is th tempeature of heat carrier fluid in the VSGHEX and regarded as the mean temperature of inlet temprature T_{pin} and outlet temperature T_{pout}. The temperature T_{s0} is the initial ground temperature.

In addition, in ortder to take into account the cost, the heat injection rate per cost q_c as expressed in Equation(10) is intruced.

$$q_c = q'_p/C \tag{10}$$

Table 2 Calculated conditions

Heating	4380 h
Heating interval	24 h(continuous), 12 h, 8 h
Heating rate [W]	500
Flow rate [L/min]	7.2
Type of GHEX	VSGHEX
Effective depth of GHEX [m]	4
Spiral pipe diameter [m]	0.2 ~ 0.7
Spiral pipe lenght [m]	50 ~ 250
Pipe outside diameter [m]	0.026
Pipe inside diameter [m]	0.032
Pipe thermal conductivity [W/m/K]	0.4
Grout effective thermal conductivity [W/m/K]	1.8
Effective thermal conductivity [W/m/K]	1.8
Density [kg/m^3]	1500
Specific heat [kJ/kg/K]	2.0
Undisturbed ground temperature [^{o}C]	14.5

3.2 Result and discussion

Figure6 compares q'_p and q_c according to the spiral diamter. The value q'_p increases if the spiral diameter becomes larger from Figure6. However, the value q_c does not becomes larger in regard to the increase of spiral

diameter. The percentage increase of cost C is larger than the one of q'_p when the spiral diameter is changed from 600 mm to 700 mm.

Figure7 is the calcualtion result of q'_p and q_c according to the total lenght of pipe. In this case study, the increase effect of q'_p by changing total length of pipe is small. Therefore, the value q_c is larger when the total length is smaller. As the result, the optimum specifications in this study are the sprial diamter of 600 mm and the total lenght of 50 m.

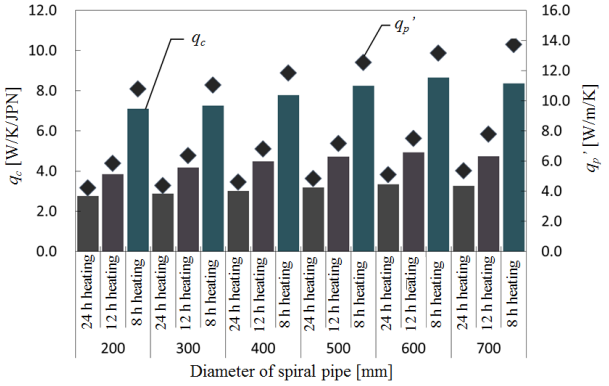


Figure 6 q_p' and q_c according to spiral diameter

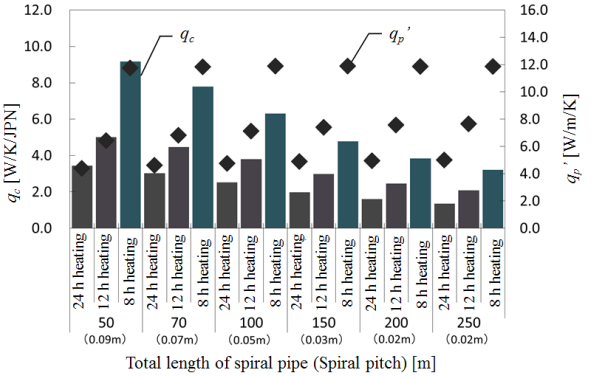


Figure 7 q_p' and q_c according to total length of spiral pipe

4. Estimation of number of vertical spiral ground heat exchangers for residential house

4.1 Calculated condition

In order to estimate the number of VSGHEXs that the GSHP system applying can be operated with high efficiency for long term, the calculateion with the simulation tool was conducted by using the parameters shown in Table3. Also, the specification of heat pump unit shown as Table4 was given as the calcualtion condition.

Sapporo and Sendai, Tokyo, Fukuoka in Japan are selected as the subject city. The residential houses have high thermal insulation performance that satisfies the next generation low energy criterion in Japan and the higher thermal insulation performance, respectively. Figure8 shows the plan view of residencial house. Hourly heat loads calculated by the softwaer (AE-CAD/Simheat) were given. Table5 shows the maximum heat load and the annual heat load. The number of required VSGHEXs was estimated by using the simulation tool under the condition, $T_{pout} > 0$ ºC, $T_{pout} < 35$ ºC ($T_{pout} > -5$ ºC, $T_{pout} < 35$ ºC in Sapporo). In addition, system COP (SCOP = seasonal heating (cooling) output / seasonal electirc power of compressor and circulating pumps) was calculated with considering the number of VSGHEX.

Table3 Calculated conditions

City	Sapporo, Sendai, Tokyo, Fukuoka
Flow rate [L/min]	7.2
Type of GHEX	VSGHEX
Effective depth of GHEX [m]	4
Borehole diameter [m]	0.2 ~ 0.7
Spiral pipe diameter [m]	0.6
Pipe outside diameter [m]	0.026
Pipe inside diameter [m]	0.032
Pipe thermal conductivity [W/m/K]	0.4
Grout effective thermal conductivity [W/m/K]	1.2, 1.8
Effective thermal conductivity [W/m/K]	1.2, 1.8
Density [kg/m^3]	1500
Specific heat [kJ/kg/K]	2.0
Undisturbed ground temperature [^{o}C]	10.5, 14.5, 16.5, 17.5

Table4 Condition of heat pump unit

Water source heat pump chiller	
Rated heating output [kW]	5.5
Rated electric power for heating [kW]	1.4
Rated cooling output [kW]	5.6
Rated electric power for cooling [kW]	1.4
Water temprature for heating [^{o}C]	40
Water temprature for cooling [^{o}C]	10
Flow rate in the primary side [L/min]	12.5
Electric power of pump in the primary side [kW]	0.02
Flow rate in the primary side [L/min]	20
Electric power of pump in the primary side [kW]	0.06

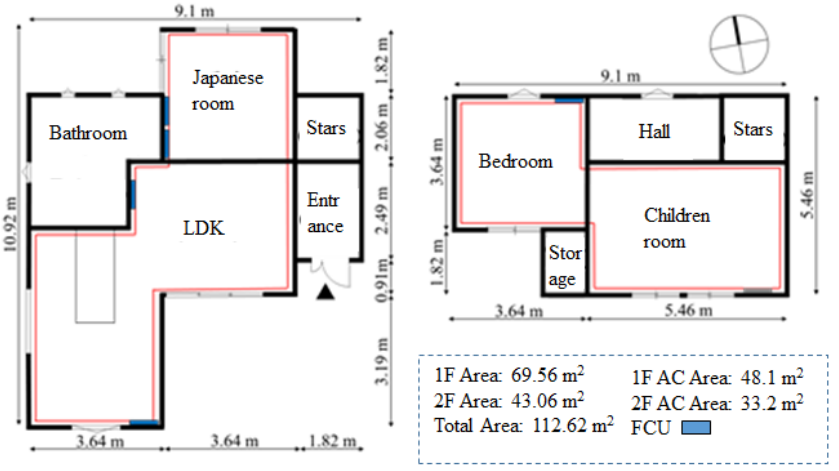


Figure 8 Plane view of residential house

Table5 Condition of thermal load

City	Heat loss coefficient [W/m^2/K]	Schedule of AC		Schedule of AC		Schedule of AC	
		Heating	Cooling	Maximum [kW]	Total [kWh]	Maximum [kW]	Total [kWh]
Sapporo	1.0	24 h (continuous)		3.58	4112	0	0
	1.6			4.59	6381	2.4	91
Sendai	1.6			3.63	3855	5.02	425
	2.4			4.98	7448	5.07	368
Tokyo	2.0			3.64	2939	4.78	1205
	2.5			4.45	4257	4.9	1175
Fukuoka	2.0			3.58	2778	5.03	1556
	2.5			4.24	3931	5.11	1515

4.2 Result and discussion

Figure9 shows the number of required VSGHEXs for the residential houses in each city under the condition, T_{pout} > 0 ºC, T_{pout} < 35 ºC (T_{pout} > -5 ºC, T_{pout} < 35 ºC in Sapporo). In the case of moderate climate region (Tokyo, Fukuoka), the number of VSGHEXs is equal or less than 10. On the other hand, the number of VSGHEXs is over 10 in the case of cold climate region such as Sapporo and the house insulation performance is almost similar to the next generation low energy criterion. In the case of higher thermal insulation performacnce in the residential house and high thermal conductivity of the ground (λ=1.8W/m/K), the number of VSGHEXs is 6. Therefore, it is effective to reduce the VSGHEXs and initial cost by installing the GSHP system to the residential house with higher thermal insulation performance. On the other hand, estimating the thermal conductivity of the ground is very important when GSHP system is designed because the number of required VSGHEXs are notable by the difference of thermal conductivity of the ground.

Heating SCOP is 4.0~4.5 and cooling SCOP is 5.0~5.3, it suggests that the GSHP system with VSGHEXs can operate with high performance. Heating SCOP in Sapporo is 3.7~3.8.

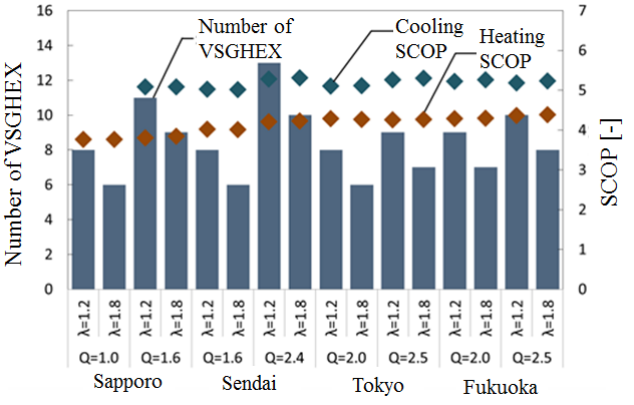


Figure 9 Number of VSGHEX and SCOP

5. Life cycle cost analysis for ground source heat pump system using vertical spiral ground heat exchangers

5.1 Calculated condition

Assuming the installation of the GSHP system with VSGHEXs, the life cycle costs were calculated. Table6 is the condition for calculation and Table.7 shows the equipment's initial cost and lifetime.

In this simulation, the city was Tokyo and the heat loss coefficient of residential house is 2.0W/m^2/K. The

GSHP systems were compared with ASHP sustem. In CASE0, the ASHP system was applied. In CASE1, the conventional GSHP system with borehole GHEX was used and the length of borehole was 60m. In CASE2 and CASE3, the GSHP sytems with VSGHEXs were applied. The difference of CASE2 and CASE3 is the thermal conductivity of ground (1.2 W/m/K for CASE2, 1.8 W/m/K for CASE3) and the number of VSGHEXs (8 for CASE2, 6 for CASE3). It is assumed that the excessive initial costs of GSHP system compared to the ASHP system is paid with a loan at 1% per year. The pipe cost of VSGHEX is 20,000 JPY, the antifreezing fluid cost is 10,000 yen, and the drilling cost is 30,000 JPY. Therefore, the total cost for one VSGHEX is 60,000 JPY.

Table6 Condition for life cycle cost calculation

	Heat pump	Heat loss coefficient [W/m^2/K]	Ground effecive thermal conductivity [W/m/K]	Number of GHEX	Heating SCOP [-]	Cooling SCOP [-]
CASE0	ASHP	2.0	-	-	2.5	4.0
CASE1	GSHP		1.5	1 (60m)	4.0	5.0
CASE2	GSHP		1.2	8	4.1	5.2
CASE3	GSHP		1.8	6	4.1	5.3

Table7 Life time and initial cost

	Equipment	Life time	Initial cost [JPY]
GSHP system	GSHP unit	15	600,000
	VSGHEX [/number]	60	60,000
	Borehole GHEX [/m]	60	10,000
ASHP system	ASHP unit	10	500,000
Secondary side	FCU	15	60,000
	Piping + piping works	30	400,000

5.2 Result and discussion

Fig.10 shows calculation result of life cycle cost. As a result, the GSHP system's cost become lower than the ASHP's cost in 10 years. In 15 years, GSHP cost exceed ASHP cost due to the replacement of GSHP unit, but GSHP life cycle cost has been lower than ASHP cost since 20 years. As a result this paper concludes GSHP system with VSGHEX is highly competitive at the point of view of economy in the case that VSGHEX cost is 60,000 or less.

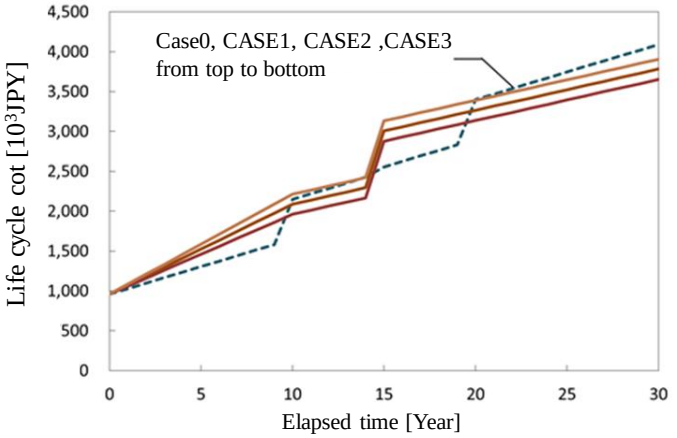


Figure 10 Comparison of life cycle cost

6. Conclusion

1) The paper developed new calculation model of VSGHEX and it was installed to the simulation tool for the GSHP system.
2) By using the simulation tool, the optimum condition of spiral diameter and total pipe length of VSGHEX were founded as 0.6m and 50m, respectively.
3) Assuming the installing the GSHP system with VGHEXs to the residential house, the number of required VGHEXs was estimated. If the residential houses have the higher insulation performance that exceed the next generation low energy criterion, the required VSGHEXs is less than 10.
4) In Tokyo, the life cycle cost of GSHP system with VGHEXs is lower than the one of ASHP system, so that GSHP system have the potential of installing at the point of economic side.

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NOMENCRATURE

A: Area[m^2], a: Thermal diffusivity [m^2/s], C: Installation cost per length [JPY/m], d: Diameter [m], E: Electric power consumption of heat pump [W], T: Temperature [^oC], m: Volume flow rate [m^3/h], h: Convection heat transfer coefficient [$W/m^2/K$], k: Thermal gradient by logarithm approximation equation [K], l: Length [m] or depth [m], Q: Amount of Heat [W], q: Heat extraction rate per length [W/m], q': Hear extraction rate per

length and temperature difference [W/m/K], q_c: Hear extraction rate per cost [W/JPY/K], r: Radius [m], t: Time [s], ρ : Density [kg/m^3], λ : Thermal conductivity [W/m/K]

Subscript

b: Borehole, *core*: Grout at core part, *f*: Fluid, *hp*: Heat pump, *in*: Inlet, *out*: Outlet, *p*: Ground heat exchanger, *p1*: pipe1, *p2*: pipe2, *s*: Soil, *shell*: Grout at shell part, *w*: Heat carrier fluid (water or antifreezing fluid), *u1*: Outside of the pipe, *u2*: Inside of the pipe, *1*: GSHP primary side, *2*: GSHP secondary side