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Operation Data Analysis of Shallow Depth Ground-Source Heat Pump System at Ogatamura and Takanosu, Akita Prefecture, Japan

Shinji Yamaguchi[1] and Isao Takashima[2]

Faculty of Eng. and Resource Science, Akita University, 1-1 Tegata Gakuencho, Akita, 010-8502, Japan

[1]dsy@ipc.akita-u.ac.jp; [2]takasima@ipc.akita-u.ac.jp

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ABSTRACT

In Europe and North America, the ground-source heat pump system widely spreads as a method of space heating and cooling system for its advantage in the environment and economy. However, in Japan, though there are some examples of introducing the ground-source heat pump system into facilities for researches and public facilities, it is not the condition where the system spreads in general private houses. This is mainly due to high drilling cost.

This paper examines the usefulness of shallow depth ground-source heat pump system that may supplement the defect of the drilling cost. By analyzing experimental data obtained at the experimental facility in Ogatamura village, the usefulness of the system is discussed. The numerical model for another experimental facility in Takanosu town is constructed and the optimum operating condition of the system is also discussed.

1. INTRODUCTION

In Europe and North America, the ground-source heat pump system widely spreads as a method of space heating and cooling system for its advantage in the environment and economy. Unit number of the system is reported with 400,000 in U.S.A., 41,700 in Switzerland, 31,400 in Sweden, etc., and the number is rapidly increasing. In these countries, it can be said that the popularization has been almost achieved as a commercial base. However, in Japan, though there are some examples of introducing the ground-source heat pump system into facilities for researches and public facilities, it is not the condition where the system spreads in general private houses. These ground-source heat pump systems utilize almost the well of the 100-meter depth class. In Japan, the drilling cost is very high with 20,000 yen/m (180 US$/m); therefore, it becomes the hindrance of the ground-source heat pump system popularization. In the meantime, there are various systems on the shallow depth ground-source heat pump system that may supplement the defect of the drilling cost. For example, horizontal systems do not need the drilling, and it can be expected that the installation cost be dramatically lowered in Japan where the drilling cost is high. However horizontal systems have some disadvantages that they require the wide site area as well as the shallow depth temperature does not stabilize by the seasonal variation. Since the site area for housing is narrow in Japan, the unsuitable idea is general for these systems.

This paper examines the usefulness of the cascade type ground-source heat pump system that may supplement the defect of horizontal systems and the drilling cost. This system combines several vertical holes of around 4 meters depth and horizontal pipes. This system can be cheaply installed, because vertical holes of 4 meters depth can be drilled using civil engineering equipments. We experiment the system in order to examine whether it is effective in Tohoku district, which is the northern part of Japan. One system was installed in Ogatamura village in 2001 and another system was installed in Takanosu town in 2003. They are all in Akita Prefecture, Japan. This paper introduces these experimental facilities and discusses the usefulness of this system by analyzing obtained operation data. The numerical modeling of this system is also tackled. The optimum operating condition of this system is also discussed with this numerical model.

2. FIELD EXPERIMENT IN OGATAMURA

One cascade type GHP system was installed in Ogatamura village, Minami Akitagun in Akita Prefecture, Japan in 2001, and the experiment has been carried out since then (Takashima, et al., 2002). This system was constructed by trenching the ground to the 1-meter depth, drilling vertical holes of 3 meters depth, and laying pipes. They were all constructed with civil engineering equipments. For the piping, the vinyl chloride pipes are used instead of polyethylene pipes generally used because of the availability of cheap vinyl chloride U-tube in proportion to the excavation diameter of about 45 cm, and the easiness in handling the vinyl chloride tube. On the thermal conductivity, though vinyl chloride is as a half of polyethylene, it is possible to achieve synthetically the almost equal level by using the simply thick tube. The piping system is made up using 2 series of 30 mm and 40 mm diameter pipes, and the total extension is 180 m.

Reclaiming land from Hachirougata Lake makes Ogatamura village. The experiment site consists of the sandy sediment, since the lakebed sediment is distributed. The ground water level is very shallow around 1 and 1.5 m. For the underground temperature and ground water level measurement, thermometers with memories and an observation well have been installed. The thermometers are attached to the vinyl chloride pipes, and are installed 3 places in the underground of 4-meter point. In the record of 10-minute interval, the automatic data acquisition for 110 days is almost possible, because the memory can store 16,000 data points.

The construction fee for 10 vertical holes of 3 meters and the trench of 1 m depth is 200,000 yen (1,800 US$). The total construction cost for the underground heat extraction part is around 300,000 yen (2,700 US$) and 400,000 yen (3,600 US$) including the piping system, and the cost may be cheap enough for the system to spread in general private houses. The indoor piping system including the heat pump is already established, and the cost estimation is simply completed. Although domestic (Japanese) heat pumps are expensive, the system price that competes with oil heating system can be realized with imported heat pumps. In addition to the superior point in cost, the system has advantages that the construction material and equipments can be readily available and the system requires no technical difficulties. Any local construction company can handle the system just after taking short courses on the system; therefore the spreading of this system is useful for the job creation of the region. It seems that however, the cooperation of the consultant with a little advanced knowledge on subsurface geology and heat extraction quantity evaluation may be required.

The GHP system in Ogatamura village was operated for the heating system from January to May in 2003 and for the cooling system from June to September in 2003, and various data were obtained. The system was controlled by the timer. As for the heating, the system was operated from 6:00 a.m. to 9:30 p.m. in the cycle of 30-minute liquid circulation and 30-minute stop. As for the cooling, the system was operated from 7:00 a.m. to 7:25 p.m. in the cycle of 25-minute liquid circulation and 35-minute stop. Fig.1 and Fig.2 show the measured temperature for the heating and cooling operations, respectively.

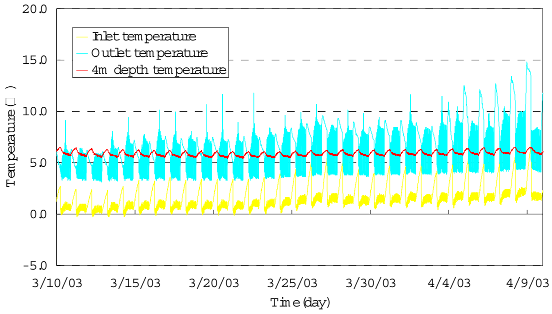

Figure 1: Temperature performance for the heating operation measured at the GHP system in Ogatamura village.

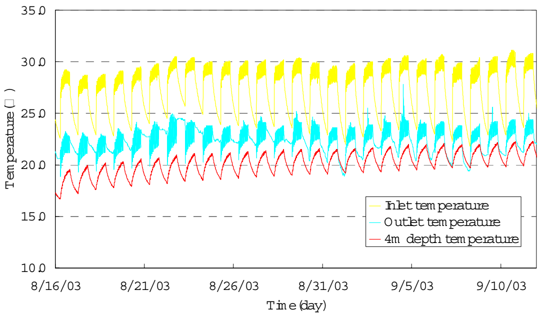

Figure 2: Temperature performance for the cooling operation measured at the GHP system in Ogatamura village.

As for the heating operation, we analyzed 1-month temperature data including those in the middle of March when the underground temperature lowered most in the year. The temperature of the secondary circulating liquid heated by heat pump in this period reached about 40 C, and it seems to be able to utilize it in systems such as the floor heating. Heat extraction quantity Q [kW] is obtained by the following equation,

$$Q = CF \times C \times G \times \Delta t \tag{1}$$

where CF, C, G, Δt are unit conversion factor, specific heat of circulating liquid, circulation quantity, and temperature change of circulating liquid, respectively. From equation (1), heat extraction quantity is calculated as 2.5 kW, using the data of G=546 kg/h and Δt =4 C. This data was obtained for the 2 series piping system of 40 mm and 35 mm diameter. The heat extraction quantity for the 1 series piping system can be estimated as 2.1 kW in the same way. Thus, in case of the 1 series piping system, heat extraction quantity per 1 m pipe is about 23 W.

Heat extraction performance for the cooling operation was remarkably better than that for the heating operation. The average inlet temperature of the underground system is around 25 C and 30 C as shown in Fig.2, and the outlet temperature is 7.5 C lower than that. Therefore, the heat extraction quantity is calculated as 4.8 kW based on equation (1). Though 1 series piping system was not operated for the cooling operation, heat extraction quantity per 1 m pipe is estimated as 44 W by applying the same method of analyses for the heating operation.

The difference of heat extraction quantity of the underground system between cooling and heating operation is dependent on the difference in underground and inlet liquid temperature. In the heating operation, inlet liquid temperature is around 0 C and 2 C, and the underground temperature of 4 meters depth is around 6 C and 8 C, that is the temperature difference is about 6 C. On the other hand, the temperature difference exceeds 10 C in the cooling operation. From these analyses, it can be said that the cooling operation is more efficient than the heating operation.

3. FIELD EXPERIMENT IN TAKANOSU

The other cascade type GHP system was installed in Takanosu town, Kita Akitagun in Akita Prefecture, Japan in 2003. The system started the operation on July in 2003. The GHP system installed in Takanosu town is almost the same system as that in Ogatamura village. The shovel car dug the ground down the interval of the 1 m depth where pipes were installed horizontally, and in addition, the vertical holes where pipes were vertically installed were carried out the excavation using the auger to the 3 meters depth. For the piping in Takanosu town, vinyl chloride tube is used similar to those in Ogatamura village. The diameter of the vinyl chloride is 40 mm. For the piping in Ogatamura village, 2 series were installed. However, since it was confirmed that even 1 series piping was enough effective by the experiment in Ogatamura village, only 1 series piping was installed in Takanosu town, and the total extension of the piping is about 90 meters.

The stratum in Takanosu town is made of gravel rock, black and brown clay layer down to near 1-meter depth, and changes as the mixture of coarse grain and gravel down to 4 meters depth.

Fig.3 shows the GHP system in Takanosu town. It consists of the underground heat extraction system of 6.5 m length, 2.0 m width, 4.0 m depth as well as the experimental house in which some equipments are installed. In the experimental house, there are a heat pump, a fan box, a tank (primary side) for circulating liquid which flows thorough the underground, a tank (secondary side) for the air conditioning and snowmelt. The tube made of the vinyl chloride of about 90 m overall length has been placed as shown in Fig.3. For the underground temperature measurement, thermometers with memories have been installed. Thermometers are installed attached to the vinyl chloride tube at 3 points in the depth of 4 meters. One thermometer is also installed at a point of 20 cm apart from the pipe to measure underground temperature change at the depth of 4 m. In the experimental house, thermometers are also installed to measure room temperature, outside temperature of the house, inflow and outflow liquid temperature of the primary side, and the liquid temperature of secondary side after heat exchange by heat pump. The GHP system has started the operation, and the data is being acquired. Temperature data will be analyzed in the same way of Ogatamura village.

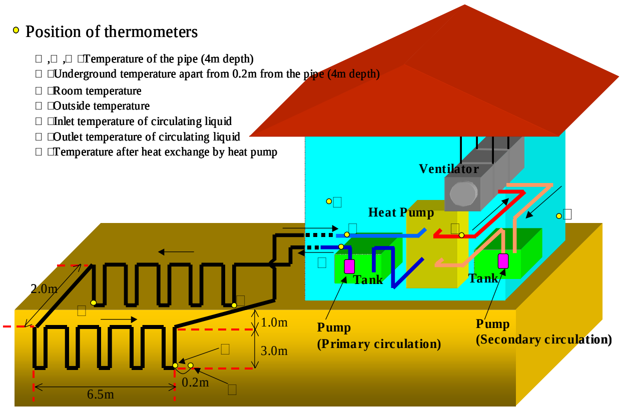

Figure 3: GHP system in Takanosu town.

4. NUMERICAL MODELING

The numerical modeling of the underground heat exchange system for the cascade type GHP system is tackled with a numerical simulator that can handle underground fluid flow and heat transfer simultaneously. Heat source or sink is applied to the numerical cells that include heat pipes.

Fig.4 shows the grid division of the underground heat exchange system, which corresponds to the system in Takanosu town. The modeled area is 14.9 m length, 11.4 m width, and 7.7 m depth.

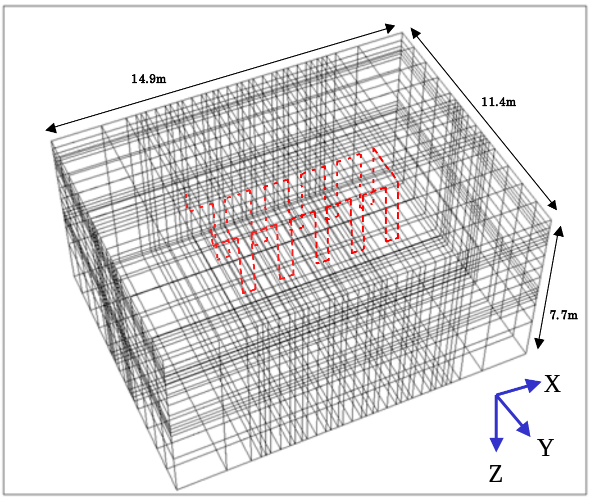

Figure 4: Grid division of the underground heat exchange system.

After some numerical investigations, this area is proved to be wide enough so that the temperature of outermost cells does not change during the simulations. Initial temperature is set as 7 C and 17 C for the simulation of the heating and cooling operations, respectively. These are average temperature measured between December in 2002 and February in 2003 for the heating operation and between July and September in 2003 for the cooling operation. The ground water level is set as 1.3 m depth and it is supposed that water saturates under the water level. Main underground properties are listed in Table 1.

Table 1: Underground Properties of the Model.

Liquid Circulation Rate (cc/s)	152
Thermal Conductivity (J/(m-day-C))	1.5×10^{5}
Thermal Capacity (J/(m^3-C))	2.3×10^{6}
Porosity (fraction)	0.2
Horizontal Permeability (m^2)	10×10^{-15}
Vertical Permeability (m^2)	1×10^{-15}

For the simulation of heating operation, temperature of circulating liquid is assumed as 2 C, which is the measured average temperature between December in 2002 and February in 2003. Through the numerical simulations, underground temperature changes are compared between continuous and intermittent operations. For the intermittent operation, the system is operated from 6:00 a.m. to 9:30 p.m. in the cycle of 30-minute liquid circulation and 30-minute stop. Fig.5 and Fig.6 show the underground

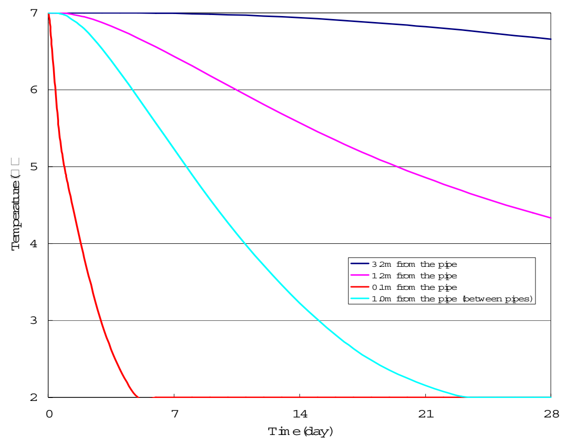

Figure 5: Underground temperature performance for the continuous heating operation.

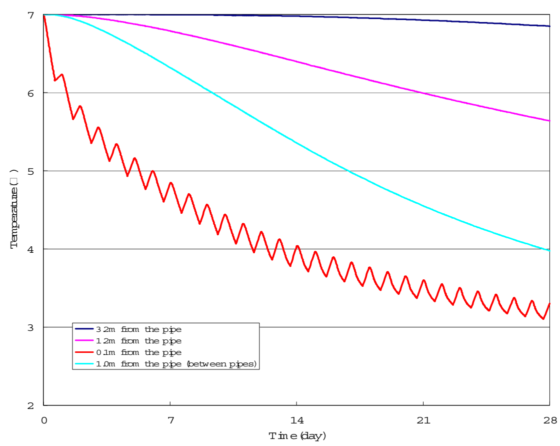

Figure 6: Underground temperature performance for the intermittent heating operation.

temperature change at the depth of 1.1 m for continuous and intermittent operations, respectively. In the case of continuous operation, ground temperature near the pipe decreases rapidly. The temperature 0.1 m apart from the pipe decreases to the same temperature of circulating liquid in about 6 days. On the other hand, in the case of intermittent operation, the ground temperature decreases slowly compared to the case of continuous operation. The temperature 0.1 m apart from the pipe shows periodic change corresponding to the operation. This means that ground temperature recovers during the liquid circulation stops. The same tendency is observed in Fig.1, which is actual measured data. Fig.7 and Fig.8 show underground temperature distribution after 7 and 28 days since the start of continuous operation, respectively. Fig.9 and Fig.10 show underground temperature distribution after 7 and 28 days since the start of intermittent operation, respectively. These figures indicate that low temperature zone expands to a large area for the case of continuous operation, while low temperature zone remains only in the vicinity of the pipe for the intermittent operation. Thus, these analyses clearly show the usefulness of the intermittent operation.

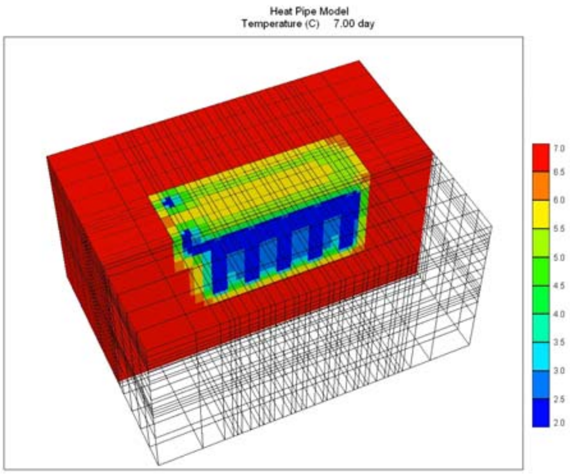

Figure 7: Underground temperature distribution after 7 days since the continuous heating operation started.

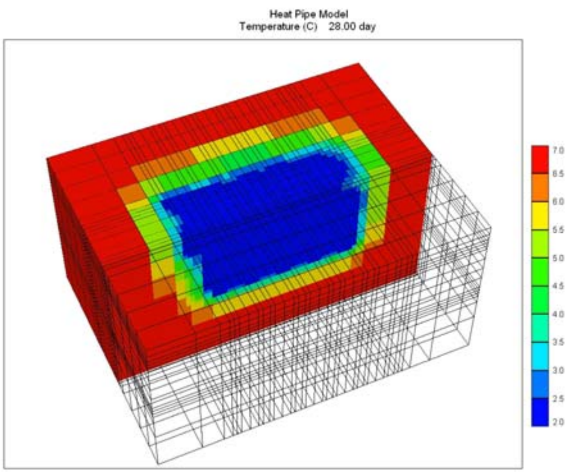

Figure 8: Underground temperature distribution after 28 days since the continuous heating operation started.

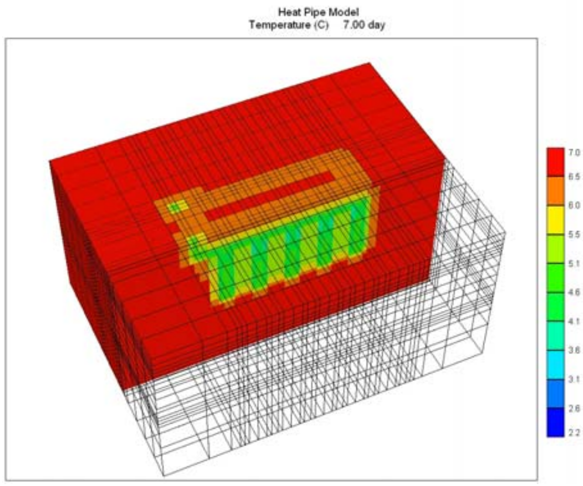

Figure 9: Underground temperature distribution after 7 days since the intermittent heating operation started.

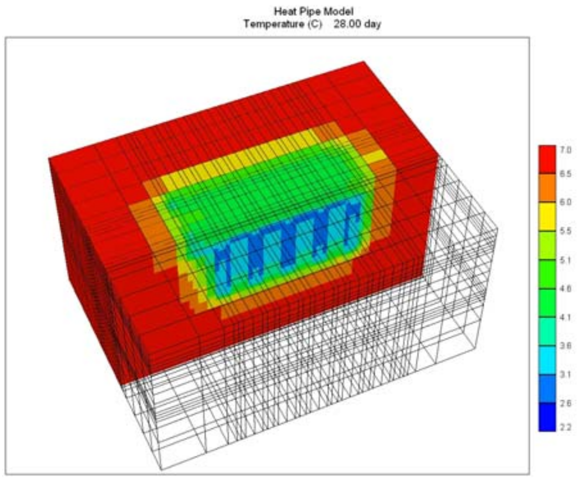

Figure 10: Underground temperature distribution after 28 days since the intermittent heating operation started.

For the simulation of cooling operation, the temperature difference is assumed as 12 C, which is the measured average temperature between August and September in 2003. Through the numerical simulations, underground temperature changes are compared between continuous and intermittent operations. For the intermittent operation, the system is operated from 7:00 a.m. to 7:25 p.m. in the cycle of 25-minute liquid circulation and 35-minute stop. Fig.11 and Fig.12 show the underground temperature change at the depth of 1.1 m for continuous and intermittent operations, respectively. In the case of continuous operation, ground temperature near the pipe rises rapidly. The temperature 0.1 m apart from the pipe rises to 25 C in about 7 days. On the other hand, in the case of intermittent operation, the ground temperature rises slowly compared to the case of continuous operation. The temperature 0.1 m apart from the pipe shows periodic change corresponding to the operation. This means that ground temperature recovers during the liquid circulation stops. The same tendency is observed in Fig.2, which is actual measured data. Fig.13 and Fig.14 show underground temperature distribution after 7 and 28 days since the start of continuous operation, respectively. Fig.15 and Fig.16 show underground temperature distribution after 7 and 28 days since the start of intermittent operation, respectively. These figures indicate that high temperature zone expands to a large area for the case of continuous operation, while high temperature zone remains only in the vicinity of the pipe for the intermittent operation. Thus, these analyses also clearly show the usefulness of the intermittent operation.

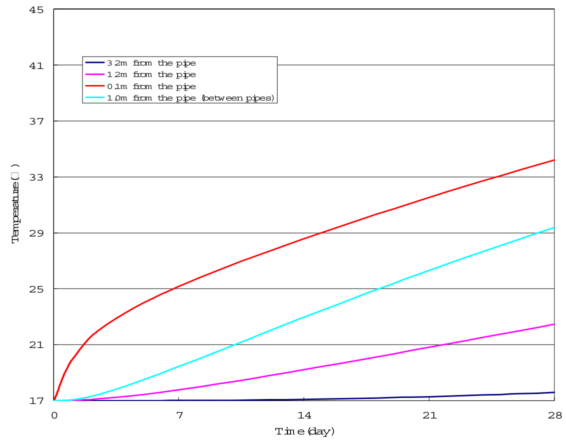

Figure 11: Underground temperature performance for the continuous cooling operation.

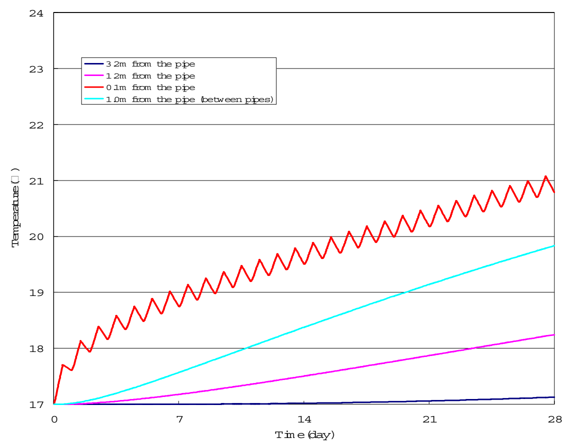

Figure 12: Underground temperature performance for the intermittent cooling operation.

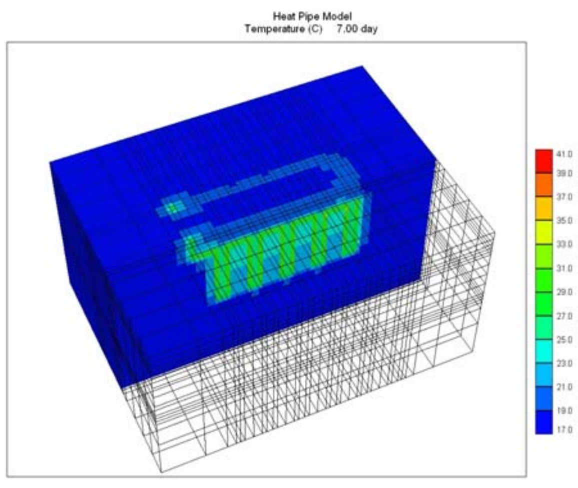

Figure 13: Underground temperature distribution after 7 days since the continuous cooling operation started.

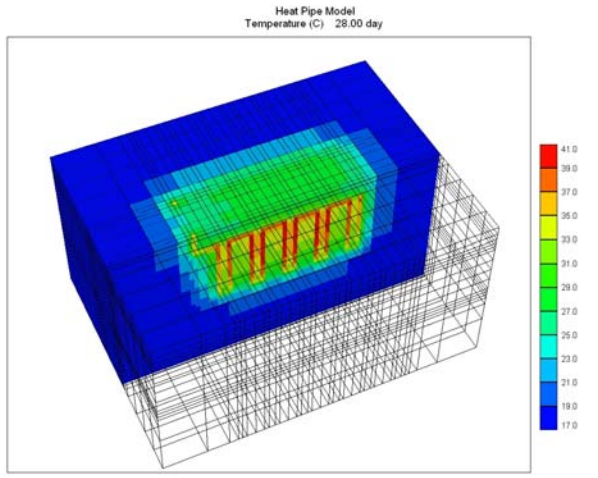

Figure 14: Underground temperature distribution after 28 days since the continuous cooling operation started.

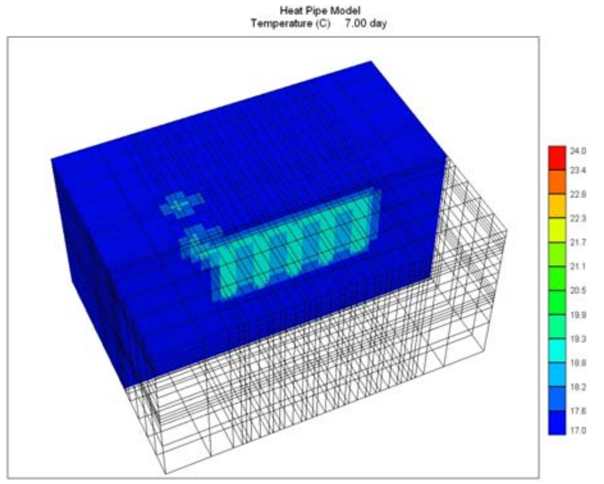

Figure 15: Underground temperature distribution after 7 days since the intermittent cooling operation started.

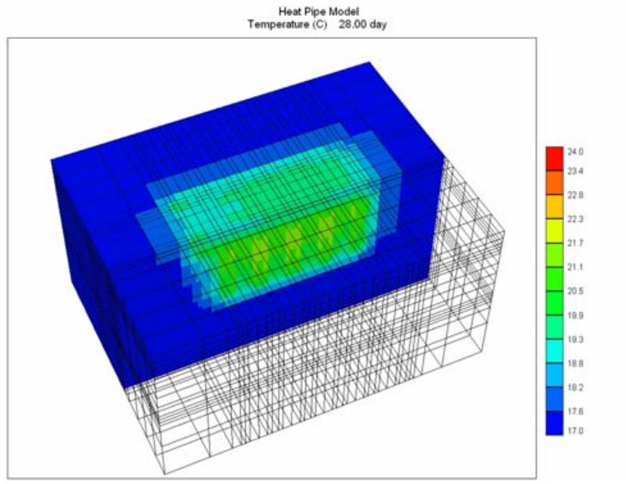

Figure 16: Underground temperature distribution after 28 days since the intermittent cooling operation started.

5. CONCLUSIONS

This paper examined the usefulness of the cascade type ground-source heat pump system that may supplement the defect of the horizontal system and the drilling cost. This system combines several vertical holes of around 4 meters depth and horizontal pipes. This system can be cheaply installed, because 4 meters depth vertical hole can be drilled using civil engineering equipments. We experiment the system in order to examine whether it is available in Tohoku district, which is the northern part of Japan. One system was installed in Ogatamura village in 2001 and the other system was installed in Takanosu town in 2003. They are all in Akita Prefecture, Japan. This paper introduced these experimental facilities and discussed the usefulness of this system by analyzing obtained operation data. From the temperature data analyses obtained at the Ogatamura village experiment GHP system, heat extraction quantity per 1 m pipe is calculated as about 23 W for the heating operation, and 44 W for the cooling operation, respectively. It is indicated that cooling operation is more effective than heating operation. The numerical modeling of the underground heat exchange system for the cascade type GHP system is tackled with a numerical simulator. Through the numerical simulations, underground temperature changes are compared between continuous and intermittent operations. After analyzing the underground temperature changes for heating and cooling operations, it is clearly indicated that the intermittent operation is a key factor for the cascade type ground-source heat pump system.

6. ACKNOWLEDGEMENTS

We would like to express our appreciation to Ogatamura village office for its permission to construct the experimental GHP system in its owned site. We would also like to express our appreciation to Kosaka Construction Company for its cooperation in constructing the experimental GHP system in Takanosu town. This research has been carried out as apart of the joint research between Akita University and Kosaka Construction Company.

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