DESIGN AND EVALUATION OF GEOTHERMAL AIR-CONDITIONING SYSTEM USING A GROUND HEAT EXCHANGER

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Abstract: In Japan, the usual geothermal air-conditioning system comprises a borehole and U-tubes that are normally made of cross-linked polyethylene pipe but, due to the very high cost of the excavation involved, this system is not widespread. We therefore constructed an economical geothermal air-conditioning system using cross-linked polyethylene pipes buried horizontally at the bottom of the building frame, instead of the usual borehole system. Usually, the ground temperature rises in summer because the air-conditioning load of buildings is radiated into the ground. Likewise, the ground temperature drops in winter because a geothermal air-conditioning system draws thermal energy from the ground. In our proposed system, the ground temperature is restored to its original level (recovers) at night. We evaluated the performance of this system after it was installed in an actual building.
The heat exchange capability of this system was nearly equal to the heat exchange capability of the usual borehole system. However, the construction cost of the ground heat exchanger of this geothermal air-conditioning system, using heat pipes buried horizontally at the bottom of the building frame, was about 1/3 that of a borehole system.

Key Words: geothermal air-conditioning system, economical and reasonable system, recovery of ground temperature

1 INTRODUCTION

The New Research Laboratory of the Kajima Technical Research Institute was built in December 2008 and started operation in spring 2009. A wide range of research on subjects such as countermeasures for global warming, biotechnology and new energies is conducted in this laboratory. More than ten leading-edge technologies that could help to reduce energy consumption and CO_2 emissions in a step-by-step manner were applied to this building to ensure efficient use of energy and enable various renewable energy sources to be utilized. The building itself serves as a functional research laboratory that gives us the opportunity to refine our leading-edge technologies in order to achieve further progress in the field of technological development. As one of the green technologies, an air-conditioning system using renewable energy sources such as solar energy, sunlight, geothermal energy and underground water was designed and its performance was evaluated. The overall concept of this system is illustrated in Figure 1.

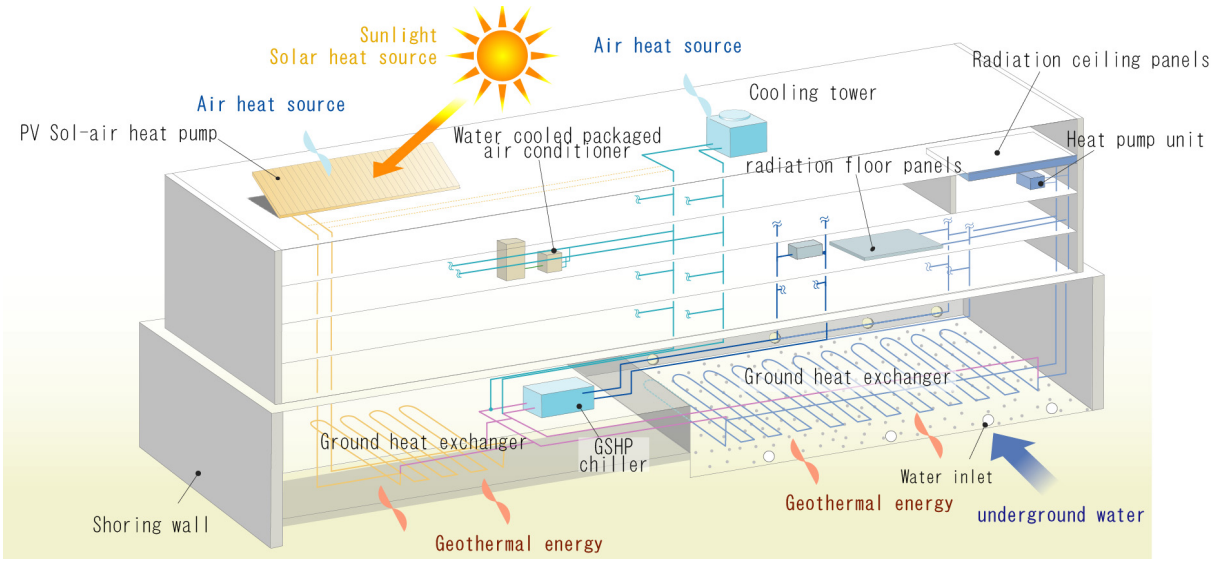


Figure 1: Overall Concept of Air-conditioning System using Renewable Energy

2 AIR-CONDITIONING SYSTEM USING RENEWABLE ENERGY

We constructed the air-conditioning system so that it could make use of multiple renewable energy sources, such as geothermal energy, solar, sunlight, underground water and the like.
Geothermal energy is used as a heat source and heat sink for the Ground Source Heat Pump system (hereinafter referred to as GSHP utilization). Moreover, geothermal energy can be used directly, without heat pump water chiller operation, as a cooling source for the radiant cooling system within the room. The water is circulated between the ground heat exchanger and radiation ceiling panels to discharge heat into the ground (hereinafter referred to as direct geothermal energy utilization). In geothermal energy utilization, since the ground temperature around the ground heat exchanger goes up during cooling operation (and goes down during heating operation) the thermal capacity of the ground will gradually become saturated. To avoid this, in our proposed system, the ground temperature recovers to a level close to the initial temperature on a daily basis.
We selected two different ways of constructing a ground heat exchanger.
In the first, the system was constructed to expedite the “natural recovery” of the ground temperature by means of natural underground water flow (assuming that an underground stream is available).
The other system used was “forced recovery”, which is adopted where no underground water flow is available. The ground temperature raised during cooling operation is then actively cooled down using the heat pump system.
In addition, a PV Sol-air heat pump system (developed by Kajima) was installed which uses solar heat and sunlight. With this system, the electricity generated by photovoltaic power is supplied through the system interconnection of the building. At the same time, hot water is generated by the Sol-air heat pump system utilizing solar energy, and chilled water is generated by the Sol-air heat pump system utilizing nocturnal radiation.

2.1 Geothermal Air-conditioning System

2.1.1 General system description

The ground source heat pump system comprising cross-linked polyethylene pipes buried horizontally at the bottom of the building frame (as shown in Figure 2) was used as the heat source for the air-conditioning system of the communication space referred to in the accompanying diagram as “Knowledge Street”.

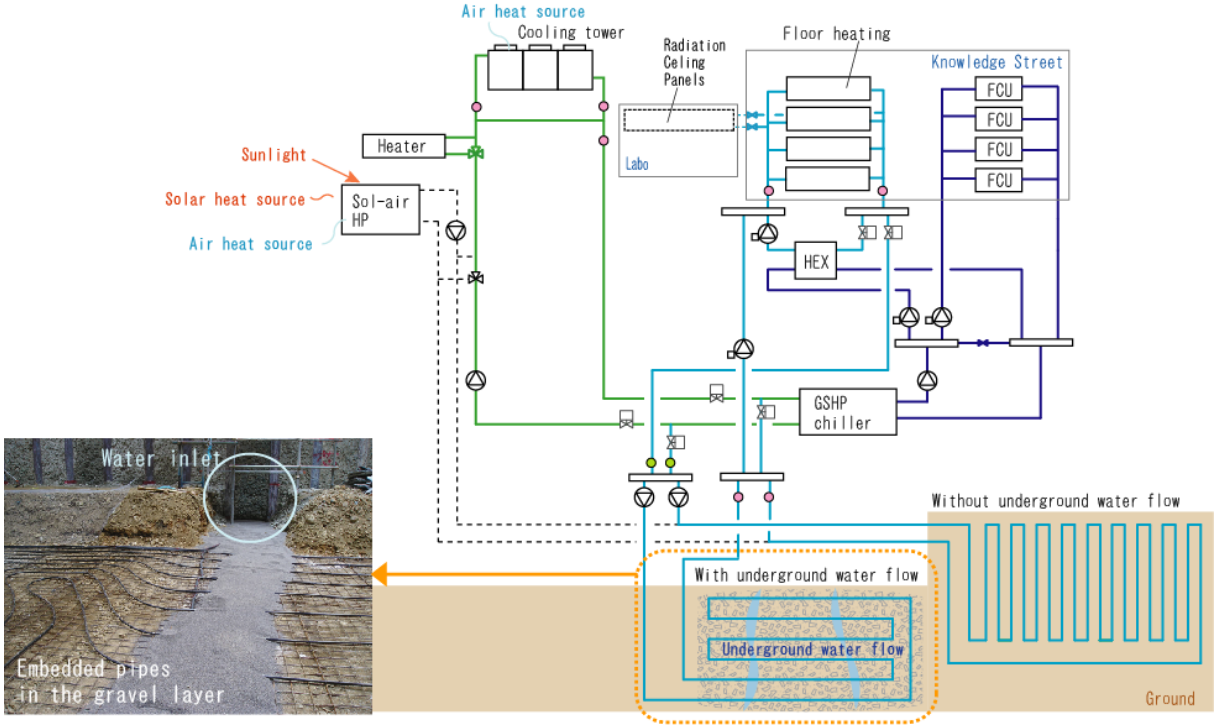


Figure 2: Conceptual Diagram of Geothermal Air-conditioning System

We constructed the air-conditioning system using cross-linked polyethylene pipes buried horizontally at the bottom of the building frame. This system was suited to the ground conditions of the site and the architectural configuration of the building. Due to the very high cost of excavation, we did not use the more common Japanese borehole system and a ground heat exchanger in cast-in-place concrete piles. Furthermore, by using a system of pipes buried horizontally, almost anyone can construct this design, not just a limited number of engineering companies with high technology.
The concept of ground temperature recovery is shown in Figure 3. In order to ensure that this sort of heat exchange system operates efficiently, the ground temperature fluctuation (caused by daytime air-conditioning operation) is recovered on a daily basis by means of “natural recovery” and “forced recovery” during the night, as described previously.

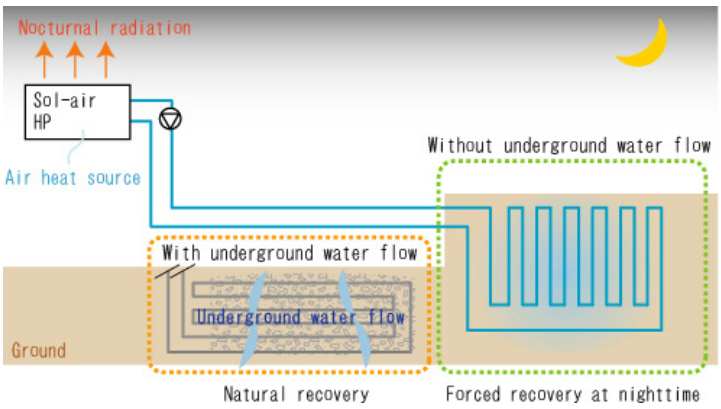


Figure 3: Conceptual Diagram of Ground Temperature Recovery at Night

[Acceleration of “natural recovery” by using underground water flow]
At the design stage, it was confirmed that an underground water flow was present around the level of the building frame (10 meters from the ground surface).

In order to take full advantage of the underground stream for geothermal energy utilization, the heat exchanging pipes were embedded in the gravel layer. The groundwater was then allowed to seep into the gravel layer through holes opened up in the shoring walls in order to increase heat exchange efficiency between the ground and the pipes. The use of underground water in this way also accelerates the recovery of the ground temperature when the air-conditioning system is not in operation.

[“Forced recovery” of the ground temperature where underground water flow is not available]
Assuming that geothermal energy will also be used in areas where underground water flow is not available, a different design was adopted with the heat exchanging pipes embedded in the leveling concrete. In this system, the level at which the pipes were embedded in the leveling concrete was shallower (8.5 meters from the ground surface) than that used for pipes in the gravel layer. At night, the Sol-air heat pump system was run to recover the ground temperature and the chilled water generated by the Sol-air heat pump system was circulated in the ground to cool it.

2.1.2 Operation mode of heat source system used in air-conditioning

In order to effectively utilize geothermal energy throughout the year, the operation modes of the heat source system are selected by an automatic control system, as shown in Figure 4. The operation mode selected is based on the temperature of the water which is circulated in the horizontally embedded pipes. During cooling, when the circulating water temperature is lower than 18℃ (an appropriate temperature for the radiant cooling system) the direct geothermal energy utilization mode is selected and when it is higher than this, the GSHP utilization mode is selected. When the circulation water temperature is higher than 30℃, the GSHP unit will run as a water-cooled chiller by means of the cooling tower. During heating, when the circulation water temperature rises above 8℃ the GSHP utilization mode is selected. When the temperature is lower than this, the auxiliary heat source systems, such as the heating equipment (gas fired vacuum type boiler and Sol-air heat pump system), start to run.

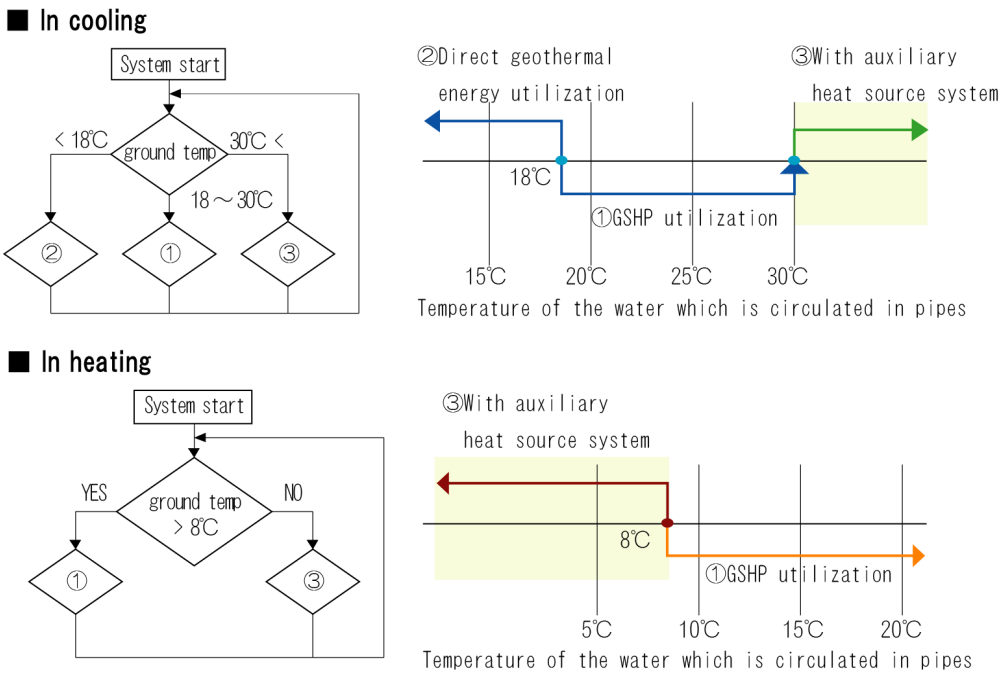


Figure 4: Conditions for Operational Mode Selection

2.2 Actual Performance Results of Geothermal Utilization

2.2.1 Advantages of geothermal energy use

During cooling, the lower the temperature of the cooling water into the heat pump, the higher the efficiency of the heat source system. The outside air wet bulb temperatures and the underground circulating water temperatures measured from May through October 2009, are shown in Figure 5. The circulating water temperatures were lower than the outside air wet bulb temperatures from June to September. During this period, the operational efficiency of the heat pump using geothermal energy could, therefore, be higher than that using the cooling tower. The outside air temperatures and underground circulating water temperatures from November 2009 to April 2010 are shown in Figure 6. The circulating water temperature was maintained at a fairly constant level whereas the outside air temperature fluctuated markedly. Therefore, the geothermal heat pump could run more efficiently than the air source heat pump water chiller.

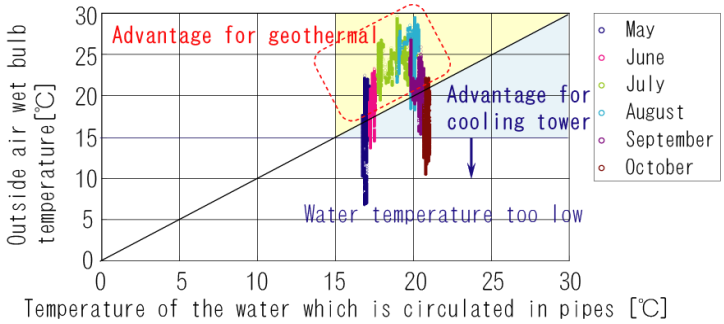


Figure 5: Outside Air Wet Bulb temperatures and Underground Piping Circulating Water Temperatures

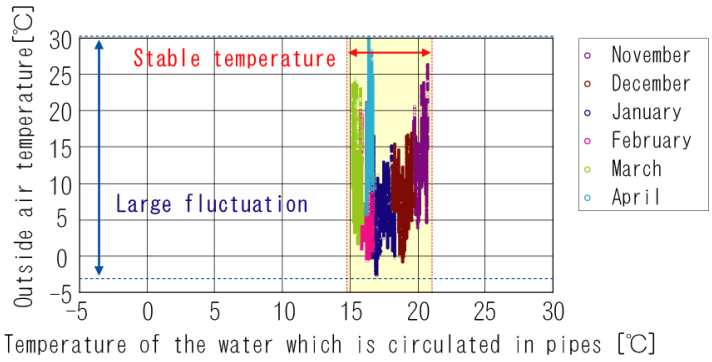


Figure 6: Outside Air Temperatures and Underground Piping Circulating Water Temperatures

2.2.2 Actual performance results for geothermal energy utilization

The actual amount of geothermal energy utilization on July 9, 2010, is shown in Figure 7. The average amount of geothermal heat exchange capability utilizing underground water flow was 16.9 kW (meaning that the heat exchange capability per unit length of embedded pipe was 21.4 W/m). The geothermal heat exchange capability obtained using conventional U-shaped tubes is said to be approximately 40 W/m. Therefore, the heat exchange capability of the proposed system is nearly equal to the heat exchange capability of U-shape system (since 1 meter of U-shaped tube is equivalent to 2 meters of single tubes). The excavation costs are said to be from 8,000 to 15,000 yen per meter. The cost of unit energy utilization will, therefore, be 300 yen/W for the borehole + U-shaped tube system, including the materials and labor costs, whereas the unit cost of our horizontal embedding pipe system is

90 yen/W, which means we have constructed a more economical geothermal energy utilization system.

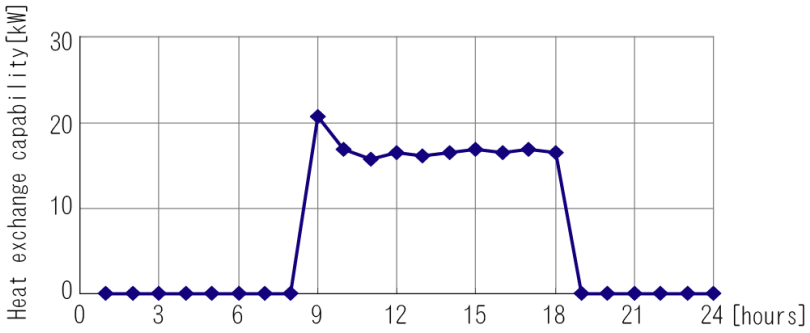


Figure 7: Actual Geothermal Energy Utilization (July 9, 2010)

2.2.3 Geothermal heat pump water chiller performance results

For one week from July 9, 2010, the heat pump water chiller was operated in GSHP utilization mode. COPs of the chiller (alone) are shown in Figure 8. These COPs were calculated on the basis of temperature and flow quantity at the inlet/outlet for the condenser water and measured the power consumption of the geothermal heat pump water chiller. The average COP value obtained for the heat source plant was approximately 4.2.

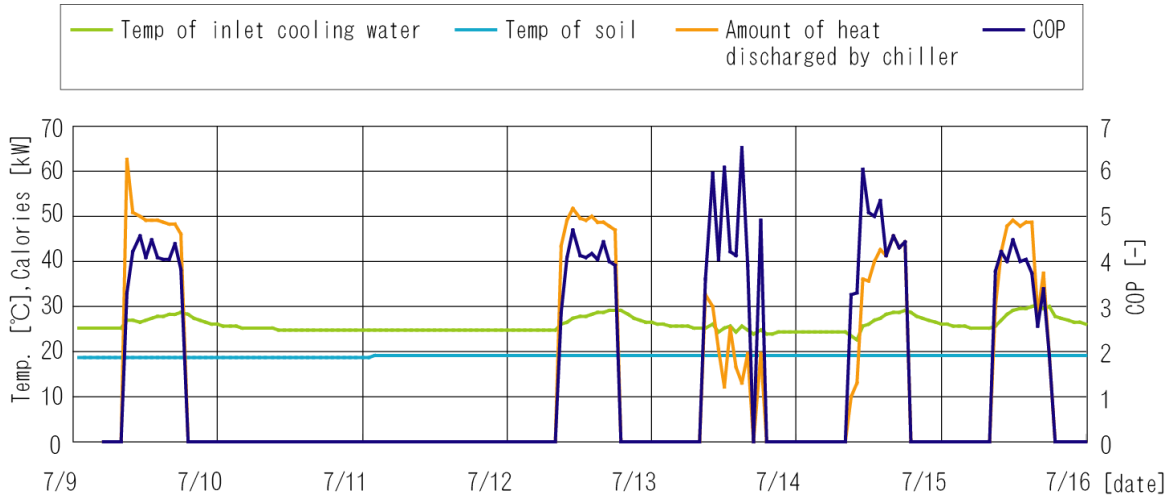


Figure 8: COPs for Geothermal Heat Pump Chiller

2.2.4 Effects of groundwater usage, by means of measurement and simulation

The level of underground water flow was measured around the circumference of the building. Results showed that for 9 months of the year, from January 2009 to December 2009, underground water flowed into the layer where the pipes were embedded. It was concluded that groundwater could, therefore, be used effectively for 75% of the year.
We created a model for heat transfer analysis simulation and studied the improvement in heat exchange efficiency obtained using underground water flow. We used the finite-element simulation system called FEFLOW. This system is based on Darcy's law for flow. In the simulation the level of underground water flow and the hydraulic conductivity of the ground were used the measured values on site. The thermal conductivity of the ground was used a general value (1.5W/mk).

As shown in Figure 9, the results of the simulation indicated that the amount of average hourly heat exchange could be increased by 11% from 3.3 kW without an underground stream to 3.7 kW with an underground stream. It can, therefore, be concluded that the underground water flow utilization system employed in this new Laboratory Building is an effective technique because it contributes to a significant increase in the geothermal heat exchange capability.

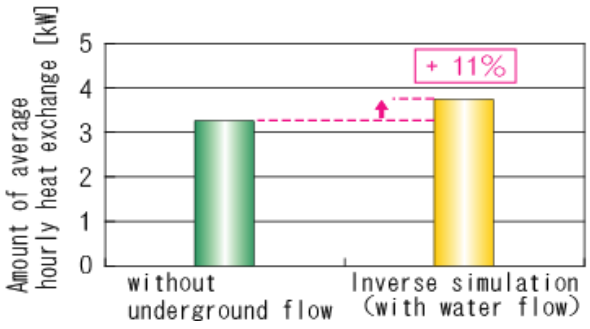


Figure 9: Simulation Results for Efficiency of Underground Water Flow

2.3 The PV Sol-air Heat Pump System

2.3.1 General system description

During heating, the Sol-air heat pump system vaporizes a refrigerant with the Sol-air panel that is installed outdoors, and gains a heat from solar radiation and air. During cooling, it condenses a refrigerant and radiates heat by emission and a convection at night. The Sol-air heat pump system that is applied to a new Laboratory Building installs a solar photovoltaic panel on the Sol-air panel. This system is called PV Sol-air heat pump.
As for the solar energy that PV Sol-air panel absorbed, a part is converted into electricity, and the other energy is gained as heat. When there is little amount of insolation, panel temperature falls than the outdoor air temperature and panel gains a heat from air. When it assumes a clear day, these operation are shown in Figure 10. The Sol-air panels gain heat from air before the break of day, and the refrigerant compressor runs with system electricity (commercial electricity). As the amount of insolation is increasing, the Sol-air panels gain more heat from solar and ratios of the photovoltaic power generation increase. In the afternoon, as the amount of insolation is decreasing, solar heat gain and quantity of photovoltaic power generation decrease and supplement it with air fever and commercial electricity. The electric power generated by photovoltaic system is interconnected to the electric power network and consumed.

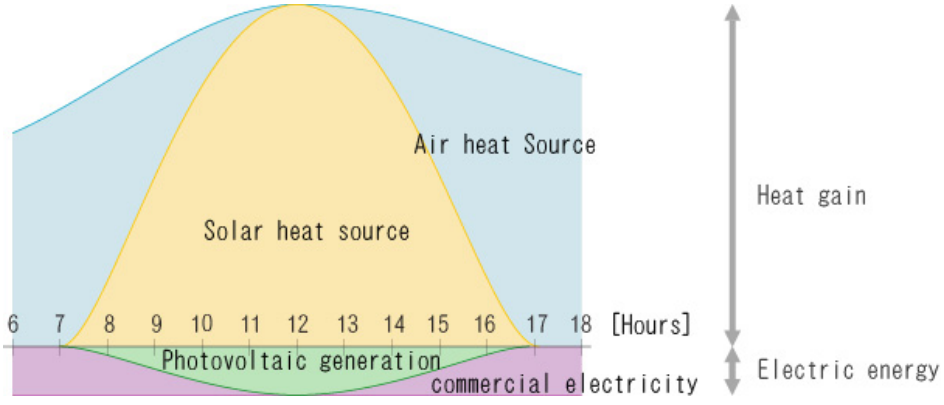


Figure 10: Image of Operation of the PV Sol-air heat pump system

2.3.2 Heat radiation in cooling operation

During cooling, the Sol-air heat pump system runs in the nighttime to recover the ground temperature using nocturnal radiation. The chilled water generated by the Sol-air heat pump system is circulated in the ground at nighttime to cool the ground. When it was raining, COPs of the Sol-air heat pump system exceeded 10 because of the cooling effect by evaporation of the rainwater at the panel surface.

2.3.3 Heat gain in heating operation

During heating, the Sol-air heat pump system runs as a auxiliary heat source of the geothermal air-conditioning system using the solar heat. About noon, COPs of the Sol-air heat pump system were around 10 with solar heat. Without the sunlight, COPs were around 6 with air heat sources.

3 SUMMARY

We constructed an air-conditioning system which can use multiple sources of renewable energy such as solar energy, sunlight, geothermal energy, underground water flow and the like.
The geothermal heat exchange capability where an underground stream was present and the actual system performance were evaluated by means of measurement and simulation. It was confirmed that the construction cost of a ground heat exchanger using heat pipes buried horizontally at the bottom of the building frame was cheaper than that of a borehole system. The heat exchange capability of this system was 21.4 W/m when an underground stream was available - nearly equal to the heat exchange capability of the usual borehole system.

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