WATER LOOP HEAT PUMP SYSTEM THAT EXPLOITS VARIOUS RENEWABLE ENERGIES SURROUNDING A BUILDING

Toshiyuki Hino, PhD, Research Advisor, Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, JAPAN;

Ryozo Ooka, PhD, Professor, Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, JAPAN;

Satoshi Yoshida, Researcher, LIXIL Technical Research Institute, Nakasato 3000, Noda-shi, Chiba, JAPAN;

Kazuo Kodama, Graduate student, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, JAPAN;

Abstract: We are developing an energy-efficient building energy system that exploits various renewable energies surrounding a building and that serves multiple kinds of thermal demands in a building, including space heating, air conditioning, and domestic hot water supply. The system links a unique heat pump named the "sky-source" to ground heat exchangers with a water loop to which dedicated water-source heat pumps to the thermal demands are connected. This paper describes the fundamental configuration of the system, prototype development of component technologies, test results and discusses possible improvements. The concept of the system and the sky-source heat pump are unique.

Keywords: domestic hot water, ground-source heat pump, HVAC, nocturnal radiation, renewable energy, solar energy, waste heat, water loop,

1 INTRODUCTION

Air-source heat pumps are expedient and satisfactory under mild weather conditions. However, on very cold days when the building heating load increases, the heating capacity of an air-source heat pump inversely decreases. Increasing the compressor speed with an inverter may help but it is insufficient. Frosting and defrosting of the outdoor unit decreases the heating capacity further. If sufficiently large capacity heat pumps were installed to meet the designed heating load, excessive start/stop operations on mild days would degrade the coefficient of performance (COP) significantly.

Air conditioning removes heat out of a room and disposes it to a heat sink (i.e. the outdoor air in the case of air-source heat pumps). The warmer the ambient temperature, the more power is required and COP decreases. The combined effects of higher air-conditioning load and lower energy efficiency cause peak load problems to the grid, which puts upward pressure on electricity prices.

Ground-source heat pumps (GSHPs) can mitigate these inherent problems of air-source heat pumps. One drawback of the GSHP is the finite usable thermal quantity because it is stocked heat of summer (or stocked coolness of winter). Thus a large soil volume is required, which is met by deep boreholes and/or a vast ground area. Additionally, for GSHP to be sustainable, the amount of thermal extraction must be roughly equal to the replenishment on an annually integrated basis. These requirements may hinder broad application of the GSHP.

Thermal energy usages in a building are not limited to space heating and air conditioning (HVAC). The domestic hot water (DHW) supply comprises the major energy consumption in a house. For these reasons, we proposed a new heat pump system.

2 RENEWABLE ENERGY UTILIZATION WITH HEAT PUMP

Solar radiation entering the Earth flows through the atmosphere and eventually leaves toward outer space as terrestrial long-wave radiation. Through this process various meteorological phenomena, known as renewable energies (REs), are generated. The source of REs commonly available around a building are insolation, ground heat, nocturnal radiation, air, wind, and rain. Table 1 explains their characteristics for utilization by a heat pump. For example, insolation is an abundant energy flow but its availability is intermittent. Utilizing these renewable energies complementarily will realize desirable heat sources and heat sinks.

Table 1: Renewable Energies and their Usability with Heat Pumping

Renewables	Usage	Availability
Insolation	Heat and Power	Abundant but Intermittent
Ground Heat	Heat Source and Sink	Stable but Finite
Terrestrial Radiation	Heat Sink	Tangible at Night
Air	Heat Source and Sink	Handy but Undependable
Wind	Boost Air-Source Ability	Unreliable
Rain	Heat Sink	Effective but Unreliable
Waste Heat	Heat Source and Sink	Quantity/Time Mismatching

3 RENEWABLE GROUND LOOP SYSTEM

3.1 System Configuration

One possible configuration of this heat pump system is depicted in Fig. 1. The system exploits REs in the atmosphere with a unique heat pump named "the sky-source" (SSHP) and RE in the ground with compact ground heat exchangers (GHXs). They are interconnected with a water loop, namely a ground loop (GL), to which decentralized water-source heat pumps for HVAC and DHW are connected. A refrigerator with a water-cooled condenser can also be connected to the GL. If the temperature of the circulating water is sufficient for the purposes, it will be directly used without a heat pump. These usages include radiant cooling and heat recovery from drainage, for instance.

To reduce energy consumption in water circulation, the GL is a closed loop with less frictional loss, and a small high-efficiency DC water pump is dedicated to and interlocked with each heat pump.

The system is unique and is known as the Renewable Ground Loop (ReGL) (Hino et al. 2013). The ReGL system can be expanded to larger systems by simply adding these components to the water loop.

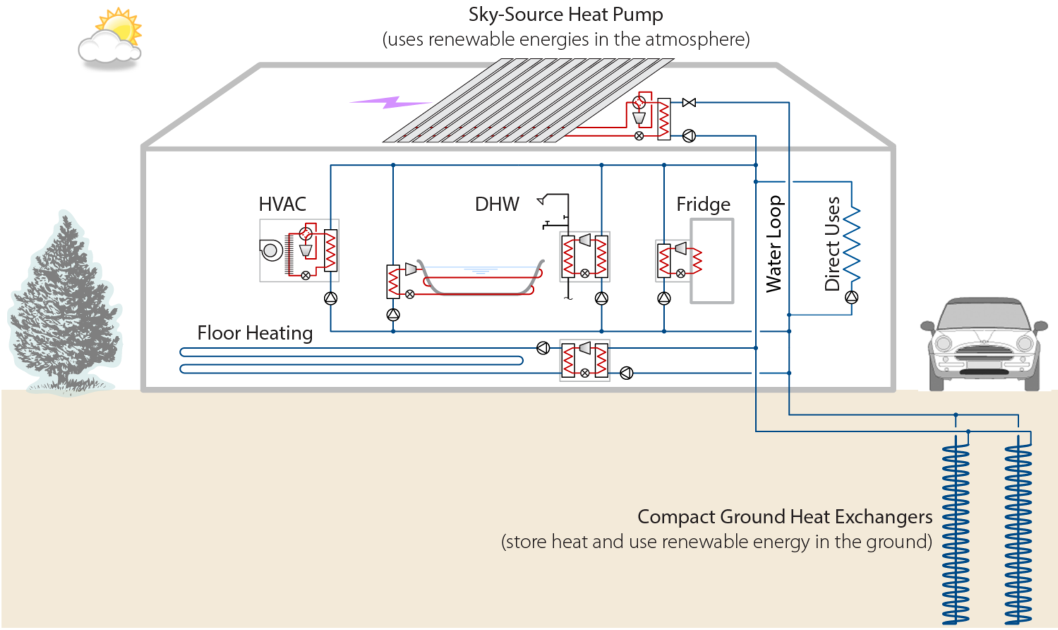


Figure 1: Possible Configuration of ReGL System

3.1 Operation Scheme

In heating space and domestic hot water supply, heat is drawn out of the loop water by evaporating the refrigerant in each water-source heat pump. Thereby the circulating water cools down and then draws heat from the surrounding soil of the GHXs. If the water temperature drops further, by several Kelvins lower than the undisturbed ground temperature, the SSHP would operate in the heat collection mode and could restore the water and soil temperature.

In air conditioning and refrigeration, the condenser heat of each water-source heat pump (and water-cooled refrigerator) is discharged to the loop water. The temperature of the circulating water rises and then heat flows into the soil surrounding the GHXs. Some heat is used by the DHW heat pump. The heat stored in the soil and held till night is removed by the SSHP operating in nocturnal radiator mode. Thus, the soil temperature is restored daily.

By exchanging heat with the GHXs and by supplementary heat collection or heat dissipation with the SSHP, loop water temperature is maintained within several degrees below or above the undisturbed ground temperature, which is about 17℃ in the Tokyo area, about 10℃ in northern, and about 20℃ in southern Japan. These temperatures are adequate as heat sources and heat sinks of the water-source heat pumps and allow high COPs in both heating and cooling cycles. Heating and cooling are supplied on demand with less electricity.

The thermal balance around the water loop is depicted in Fig. 2. The arrows indicate the heat flow directions. The cooling cycle of each HP is an input to the loop and the heating cycle of each HP is an output from the loop. The sum of the inputs rarely counterbalances that of the outputs. In the ReGL system, instantaneous imbalance is compensated with the GHX and daily-integrated imbalance is canceled with the SSHP.

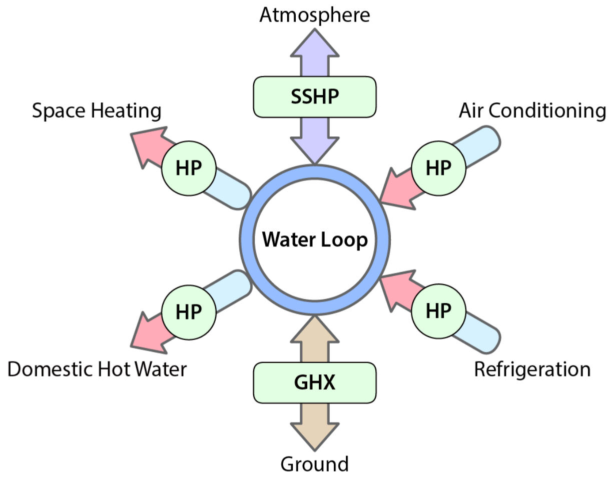


Figure 2: Thermal Inputs and Outputs around Water Loop

4 COMPONENT TECHNOLOGY

To confirm the concept, a prototype system was developed and tested at the University of Tokyo. The ReGL system consists of several component technologies, among which the sky-source heat pump is unique and may require further explanation.

4.1 Sky-Source Heat Pump

4.1.1 Solar Collector and Nocturnal Radiator

The sky-source heat pump absorbs heat by evaporating refrigerant in the outdoor (SS) panel and dissipates heat by condensing refrigerant in the same panel (Hino 1995). Figure 3 shows a prototypical SSHP module made in 2011. The SS panel area was 7 m^2 and the nominal capacity in heating and cooling the loop water was 5 kW (Table 2). A compressor unit was placed under the SS panel.

The SS panel was composed of 16 aluminum-extruded finned tubes placed in parallel. A cross section of the finned tube is shown in Fig. 4. It had a flat topside surface for solar energy collection and fins on the backside for heat exchange with the ambient air using natural drafts and wind. A refrigerant passage was located in the center. Photovoltaic (PV) cells were to be attached on the topside surface (named PV-SSHP) but were not installed in this module.

Figure 3: Sky-Source Heat Pump Module

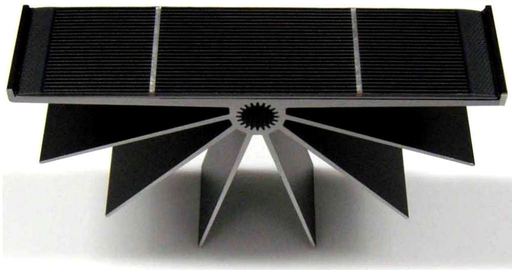


Figure 4: Cut Model of Finned Tube (PV Cell Attached on Top Surface)

Table 2: Specifications of SSHP Module

Panel Area	7.0 m^2
Panel Size	Length: 2.4 m, Breadth: 3.2 m
Panel Angle	30° facing south
Thermal Output	5 kW nominal (heating and cooling)
Working Fluid	HFC-410A
Compressor	Hermetic Swing Rotary
Expansion Device	Drainer
PV cell	(Not installed in this module)

4.1.2 Refrigeration Circuit

The refrigerant circuit of the SSHP module is depicted in Fig. 5. It employs a drainer as an expansion device, which drains condensate promptly while preventing the passage of high-pressure gas. The evaporator outlet is wet because the orifice opening of the drainer is not controlled by the superheating at the evaporator outlet. Thus, performance improvements both in the condenser and the evaporator and reliable oil return to the compressor are implemented.

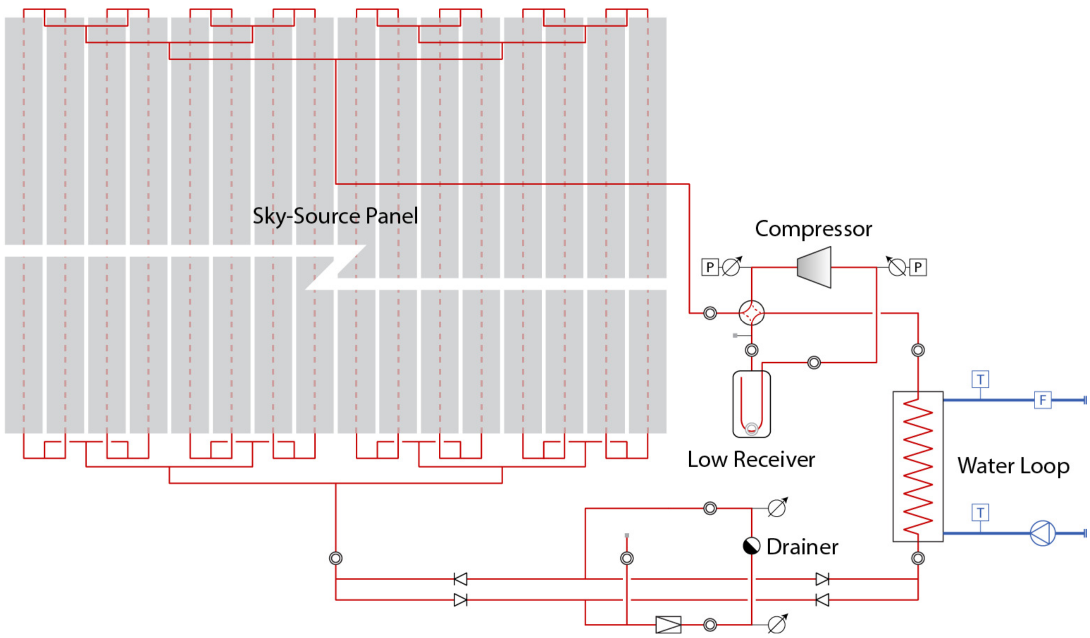


Figure 5: Refrigerant Circuit of SSHP Module

4.1.3 Panel Heat Exchange

The SS panel exchanges heat q_p [W] with the atmosphere and the sky by radiation and convection, as symbolically expressed in the following equation. A positive value means incoming heat and a negative value means outgoing heat.

$$q_p = a\left(I_{p1} + I_{p2}\right)A + \eta_{fin}\alpha\left(T_a - T_p\right)A_{fin} + \varepsilon F_{sky}\sigma\left(T_{sky}^4 - T_p^4\right)A + \varepsilon F_g\sigma\left(T_g^4 - T_p^4\right)A - \eta_{PV} I_{p1} A \qquad (1)$$

Q=c ×

where, a = solar absorbance [-], I_{p1} and I_{p2} = insolation on the top and bottom sides of the panel [W/m^2], A = panel area [m^2], η_{fin} = fin efficiency [-], α = heat transfer coefficient to air [W/m^2-K], T_a = outside air temperature [K], T_p = panel temperature [K], A_{fin} = surface area [m^2], ε = emittance of infrared (IR) radiation [-], F_{sky} = view factor to sky [-], σ = Stefan-Boltzmann constant [5.67 × 10^{-8} W/m^2-K^4], T_{sky} = equivalent blackbody temperature of sky [K], F_g = view factor to ground [-], T_g = equivalent blackbody temperature of the ground surface [K], η_{PV} = generation efficiency of photovoltaic cell [-].

Solar absorbance a and emittance ε were assumed to be 0.9 in the following data analyses. The last term in Eq. (1) was null because solar cells were not installed on the panel.

4.1.4 Collector Operation

In the collector operation, the SS panel was cooled by evaporating refrigerant to absorb the heat from the atmosphere. Operational data are plotted in Fig. 6. It was a sunny day and the outdoor temperature was about 8℃ in the afternoon and gradually fell to 5℃ in the evening. Heating output was maintained at around 5 kW for experimental purposes by manually adjusting the inverter frequencies of the compressor.

COPs were high at about 10 to 15 in the afternoon but they gradually decreased as insolation became weak toward the evening. Fluctuations of COP before 13:15 were attributable to the temperature fluctuations of the loop water, which were caused by on-off operations of the DHW heat pump.

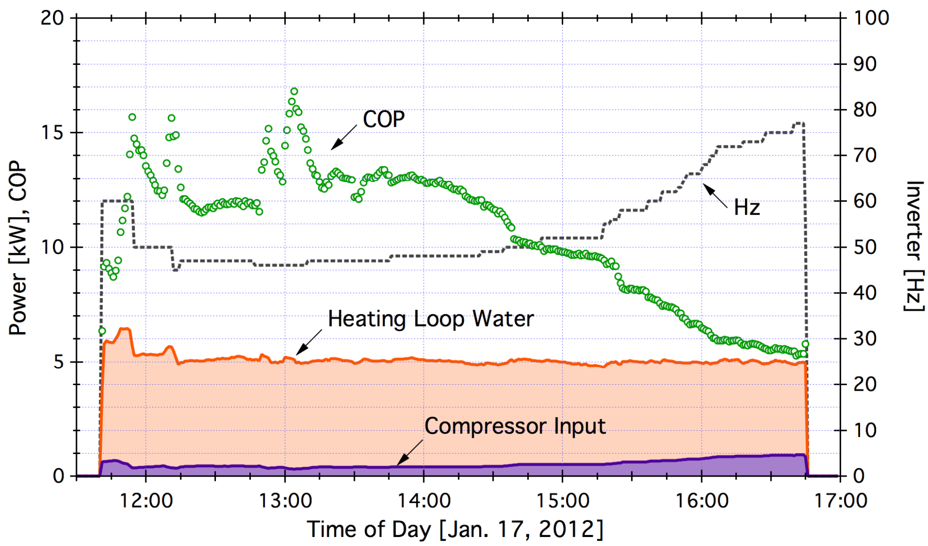


Figure 6: Collector Operation of SSHP

In Fig. 7, the "collected heat" is calculated by subtracting the "compressor input" from the "heating loop water" in Fig. 6. When insolation was strong, the "solar radiation absorbed" exceeded the "collected heat" until about 14:15 and the panel operated entirely in the "solar-source" mode and excessive solar energy absorbed by the panel was dissipated to the air. After about 14:15, the "solar radiation absorbed" fell below the "collected heat" and the difference was made up with the "air-source". In this operation, the panel temperature was lower than that of the ambient air.

The "air-source" in Fig. 7 includes IR radiation coming from the sky and the ground with simultaneous outgoing from the panel. The net IR radiation balance was plus (collecting) when the heat pump was operating and minus (radiating) when it was stopping. This difference may be caused by the temperature change of the panel but further investigations are necessary.

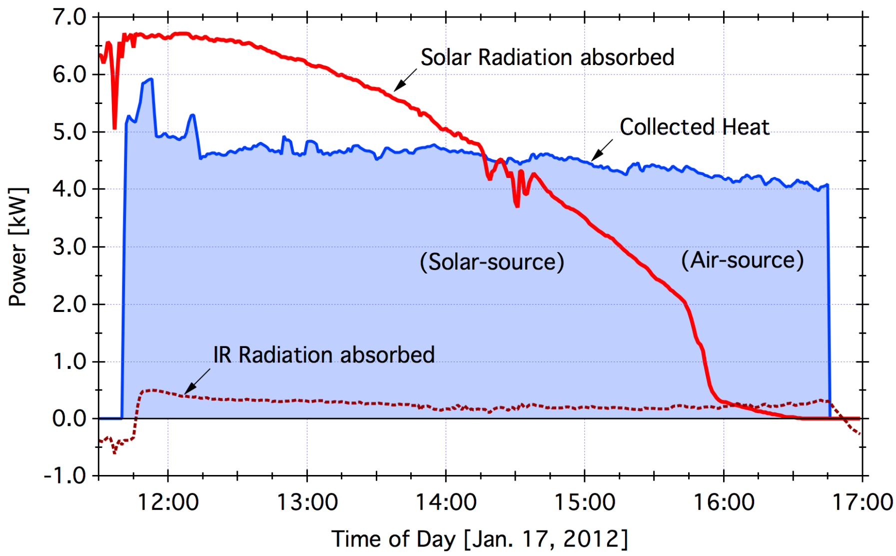
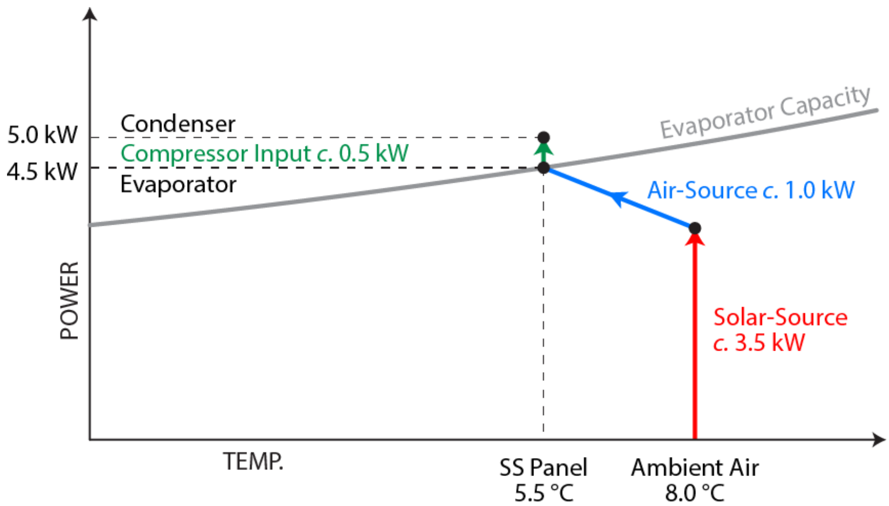


Figure 7: Collected Heat by SS Panel (Incoming Heat is Plus)

At around 15:00, the SSHP was operating in combined mode of the solar-source and the air-source. Its heating performance is roughly analyzed in Fig. 8.



COP = Condenser Output / Compressor Input = 5.0 / 0.5 = 10

Collector Efficiency = Collected Heat / Insolation on Panel = 4.5 / (3.5 / 0.9) × 100 = 116 %

Figure 8: Heating Operation in Both Solar-Source and Air-Source

The operating condition was a thermal equilibrium between the evaporator capacity and the heat collection of the panel. The former was 4.5 kW and the latter was the "solar-source" of 3.5 kW plus the "air-source" of 1.0 kW. The "air-source" was the heat flowing from the ambient air at 8.0℃ to the panel at 5.5℃. Compressor input of 0.5 kW was added to the evaporator capacity to become a condenser output of 5.0 kW and the heating COP was 10.

The collector efficiency, which is defined as the collected heat divided by the insolation on the panel, was 116%. The explanation for exceeding 100% is that heat exchange with the ambient air is a gain to the SS panel while it is a heat loss in the case of ordinary solar collectors. Higher collector efficiency allows a smaller collector area. More data are plotted in Fig. 9, in which the abscissa was determined by the following equation.

$$\left(T_f - T_a\right)/I_p \qquad [\text{K-m}^2/\text{W}] \tag{2}$$

where, T_f = refrigerant evaporating temperature, and fluid outlet temperature in the case of ordinary collectors [K], I_p = sum of I_{p1} and I_{p2}, and insolation on the collector in the case of ordinary collectors [W/m^2].

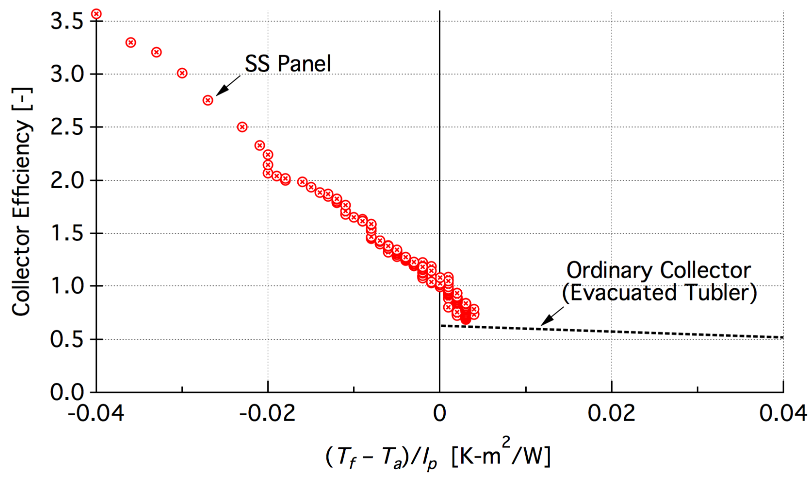


Figure 9: Collector Efficiency

The SS panel occasionally frosted on dark cold days but defrosting was not necessary throughout the test period, and the ice on the panel disappeared naturally over time.

4.1.5 Radiator Operation

The SS panel operated as a radiator to cool the loop water and the data on a cloudy night are plotted in Fig. 10. The SSHP started at 23:00 when off-peak electricity applied and stopped at around 02:45 by sensing the loop water temperature at 17℃. The cooling COPs were high just after starting but soon decreased as the SS panel became hotter. The wind velocity was low at less than 1 m/s until around 02:00, and then it increased up to 2 m/s and COP improved accordingly. It rained at around 02:30 for a short period and COP immediately rose to 10. Water evaporation on the panel was an effective heat sink.

The ratio of infrared radiation to the total dissipated heat was at most 20% on this night. It seems clouds and moisture emitted infrared radiation, which raised the equivalent blackbody temperature of the sky. On clear nights, the contribution of infrared radiation sometimes reached 30%.

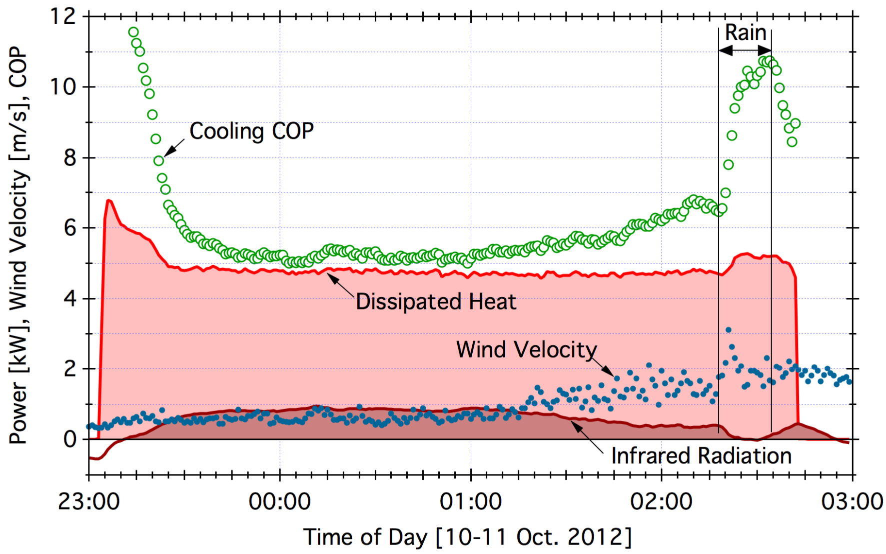


Figure 10: Radiator Operation of SS Panel (Outgoing Heat is Plus)

4.2 Compact ground heat exchanger

Daily restoration of the ground temperature with heating or cooling by the SSHP allows high-density and compact ground heat exchangers, because the thermal penetration distance in the soil is a few tens of centimeters; one digit shorter than the borehole distances of the conventional ground source heat pumps that restore the ground temperature annually. To exploit this benefit, a high-density and compact helical-coil ground heat exchanger was developed. The coil was 10 m tall and made of a high-density polyethylene corrugated 50A tube whose total length was 90 m. The coil held about 200 liters of tap water, of which the thermal energy storage would be beneficially used to supply a high power but short duration load like an on-demand DHW supply heat pump. Antifreeze solution was dispensable because heating with the SSHP protected the loop water from freezing. The coil was buried in a 12-m deep hole that was dug efficiently with an earth auger.

4.3 HVAC

A heating COP of a water-source HVAC heat pump that heats space at 21℃ using heat-source water at 15℃ was logically predicted to be 7.8. A commercially available, small-sized (3.0/2.5 kW in heating/cooling) water-source heat pump was modified and connected to the experimental ReGL system. The measured heating COP was around 5 to 7, showing room for further improvement.

A cooling COP to air-condition a room at 28℃ with a relative humidity at 40% using heat-sink water at 19℃ was logically predicted to be 12. Measured cooling COPs of the above-mentioned product were around 10, slightly less than the predicted value.

One of the causes of the above discripancies between the predicted and the measured values was attributed to the expansion device. The superheating at the outlet of the evaporator, the subcooling at the outlet of the condenser, and the amount of the refrigerant charge were hardly optimized simultaneously in both the heating and cooling cycles with a bidirectional expansion valve. A drainer used in the SSHP was considered to be a possible solution.

4.4 DHW

The thermal transportation capability of the water loop and the thermal energy storage capacity of ground heat exchangers can be beneficially exploited for an on-demand supply DHW heat pump that heats tap water up to the usage temperature (about 40℃), without losing bactericide (e.g. chlorine). This system was set up for experimental purposes and a compressor unit was placed under the basin to minimize the hot-water supply piping.

Hot water was supplied constantly by feedback controlling the compressor inverter and a COP of around 8 was observed while recovering the waste heat of the air conditioning. Start-up should be faster in order for this technology to become practical (Hino et al. 2013).

5 CONCLUSIONS AND PROSPECTS

We proposed an innovative water loop heat pump system that harvests multiple renewable energies and that meets various thermal demands in a building, called the ReGL. Through the development of the prototype system and based on its test results, we have drawn the following conclusions and describe its future prospects.

1. The combination of a sky-source heat pump (SSHP) with a ground heat exchanger (GHX) may implement complementary benefits for both parts: the SSHP can collect and radiate heat irrespective of the usage: the GHX can be compact and its burial expense may be reduced. Leveling and shifting electricity consumption will be more important in the coming smart-grid era.

2. The ReGL system may reduce energy consumption by half in comparison with ordinary air-source heat pumps. A system COP of 7 is a target in temperate climatic regions because the COP of each water-source heat pump is around 8 and further improvement is possible; a DC water pump dedicated to each heat pump consumes less than 10% of the compressor; the PV-SSHP itself is net zero, i.e. the power consumption can be compensated with the generation of its own PV cells, on an annually integrated basis.

3. The system may have wide applicability in scale and usage because the water loop can be expanded, to which decentralized heat pumps for various purposes can be connected as needed. The ReGL system is considered to be highly applicable in various climates since its heat source and sink originate in the Earth itself.

Development of the ReGL system is still in its infancy. Further experimental and analytical works should follow.

ACKNOWLEDGEMENT: This development was supported by research grants from the Ministry of the Environment of Japan.

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