THE SOL-AIR HEAT PUMP SYSTEM: RECENT DEVELOPMENT AND FUTURE EXPANSION

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Abstract: The Sol-Air Heat Pump (SAHP) has refrigerant-circulating outdoor (SA) panels with which heat is exchanged in the atmosphere by both radiation and convection. In the heating cycle, the SAHP works in solar-source and air-source mode complementarily. In the cooling cycle, the SAHP works as a nocturnal radiator. The recently developed SAHP has photovoltaic cells attached on the panels. Its operating results showed efficient use of solar energy in heat and power, but it left some room for further improvement. The future SAHP will be integrated into a ground loop system, named the ReGL, to harness various renewable energies in the atmosphere and under the ground. The ReGL system is intended to supply most of the thermal energy demands in a building, namely, space heating and cooling, domestic hot water supply, and refrigeration.

Key Words: ground source, photovoltaic, renewable, solar energy, water loop

1 INTRODUCTION

Solar energy utilization by heat pumping is an old idea but it is still a technological frontier for the future. We have been developing a solar heat pump named the Sol-Air Heat Pump (SAHP) since 1974. Its outdoor (SA) panel works as a solar-source and air-source evaporator in the heating cycle and as a nocturnal radiator by changing it to a condenser in the cooling cycle. Some of the early works were described in the literatures (Hino 1984, 1990). Although further installation of the SAHP had been absent for nearly 20 years, some research continued (Hino 1995, 1998).

As the global environmental issue is becoming serious, renewable energy utilization is getting more expectations and we considered the SAHP has high potential. The advanced SAHP should incorporate photovoltaic technology that is improving rapidly, and it would be integrated with a ground-loop system to pursuit new possibilities.

2 TECHNOLOGY

2.1 Renewable Energy Utilization

Various renewable energies are generated in the atmosphere through the process of energy flow from solar radiation to terrestrial radiation as depicted in Figure 1. Solar radiation is a natural source of heating, and we can use it directly with a solar collector or indirectly with an air-source heat pump. The SAHP harvests both.

For cooling, we are often unconscious of the terrestrial radiation and use it indirectly with an air-cooled or water-cooled condenser. Thus increased enthalpy of atmospheric air is eventually cooled by the terrestrial radiation. The SAHP directly use the terrestrial radiation along with air-cooling and water evaporation to reject heat in the cooling cycle.

Wind intensifies convective heat transfer on the SA panel in the heating and cooling cycles.

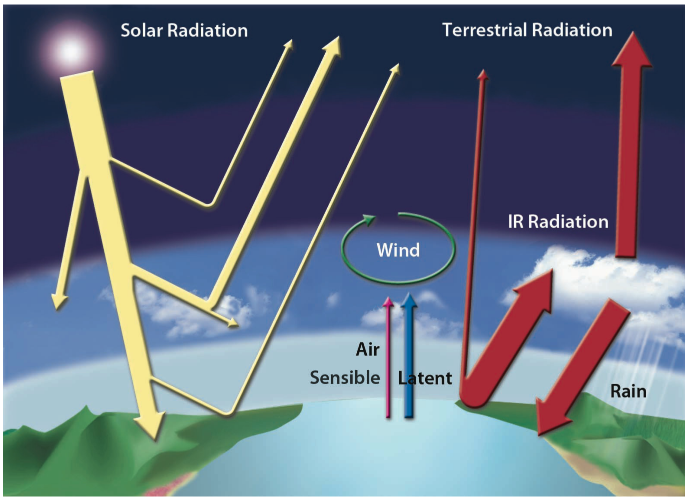

Figure 1: Origin of Renewable Energy

2.2 Sol-Air Panel

The SA panel (Figure 2) is composed of several finned tubes placed in parallel. The section of the finned tube, produced by an aluminum extrusion method, is explained in Figure 3.

Figure 2: SAHP Installed in 2009

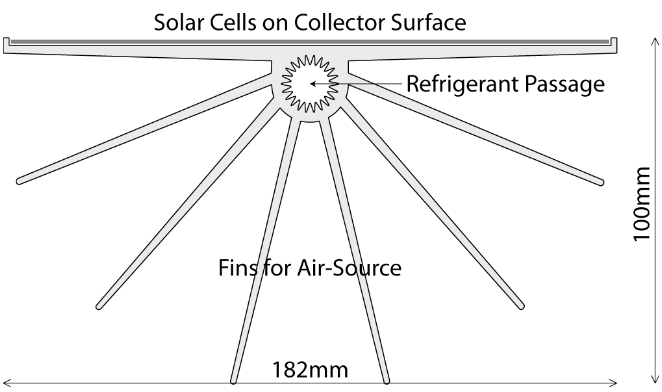

Figure 3: Cross Section of Finned Tube

Topside of the finned tube is a solar collector surface on which solar cells are attached and backside has several fins to exchange heat with air by natural convection and wind. In the refrigerant passage, liquid refrigerant evaporates in the heating cycle and gaseous refrigerant condenses in the cooling cycle.

2.3 Solar Energy Utilization

An operating condition in the heating cycle is determined as an equilibrium point between collected heat by the SA panel and thermal power of the evaporator. Adding compression energy to it makes condenser power (i.e. heating output) as illustrated in Figure 4. In this figure, the temperatures (horizontal axis) of collector and evaporator were assumed to be equal to make explanation simple.

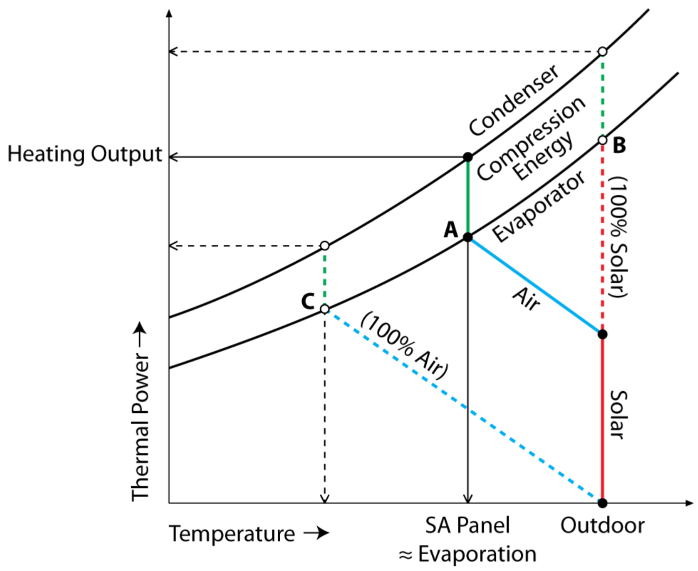

Figure 4: Explanation of Heat Collection

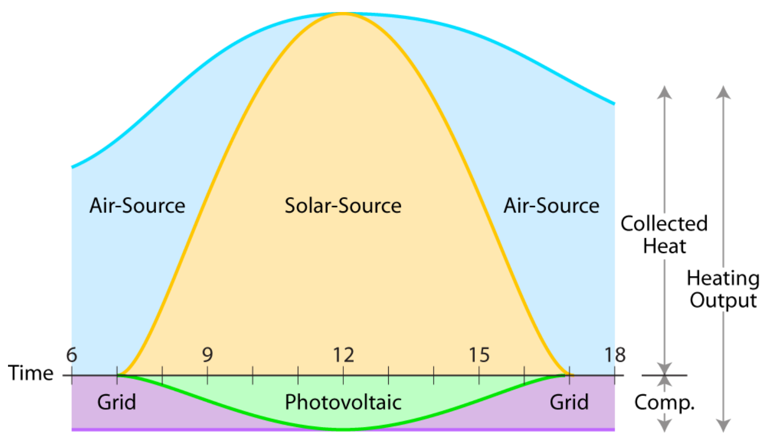

Figure 5: Hypothetical Heating Operation on a Clear Day

When insolation is about half of the maximum (say, 500 watt per square meter), solar energy is absorbed first but it cannot meet the evaporator power. This shortage is compensated with air-source capacity by decreasing the SA panel (i.e. evaporator) temperature, and the intersecting point A becomes the operating point. When insolation increases to just meet the evaporator power, no heat exchange with air takes place and the point B becomes a new operating point. If insolation is unavailable, panel temperature falls to the point C where air-source capacity of the panel equal to the evaporator power.

Heating operation on a clear day is explained hypothetically in Figure 5. Before dawn when insolation is unavailable, the SAHP works as an air-source heat pump and its compressor is driven with electricity from a grid. As insolation increases in the morning, the air-source is gradually replaced by the solar-source and the photovoltaic power reduces grid power consumption. Around noon, the SAHP works only with solar energy, both heat and power. In the afternoon, this transition is reversed.

3 APPLICATION

3.1 SAHP Module

The SAHP was applied to a new research building in Tokyo and it has been supplying a small portion of the heating and cooling load since 2009. The main air-conditioning system of the building is water-source heat pumps that are connected to a water loop. During a heating season, circulating water is maintained at around 20ºC by gas boilers. The SAHP was installed to reduce gas consumption.
Refrigerant circuit of the SAHP module is illustrated in Figure 6. Drainers (i.e. gas traps) are placed downstream of the condensers to stop gaseous refrigerant and pass condensate. Orifice of the drainer works as an expansion device. A drainer is considered superior to an expansion valve in the views of oil recovery, heat exchange, and stable operation.

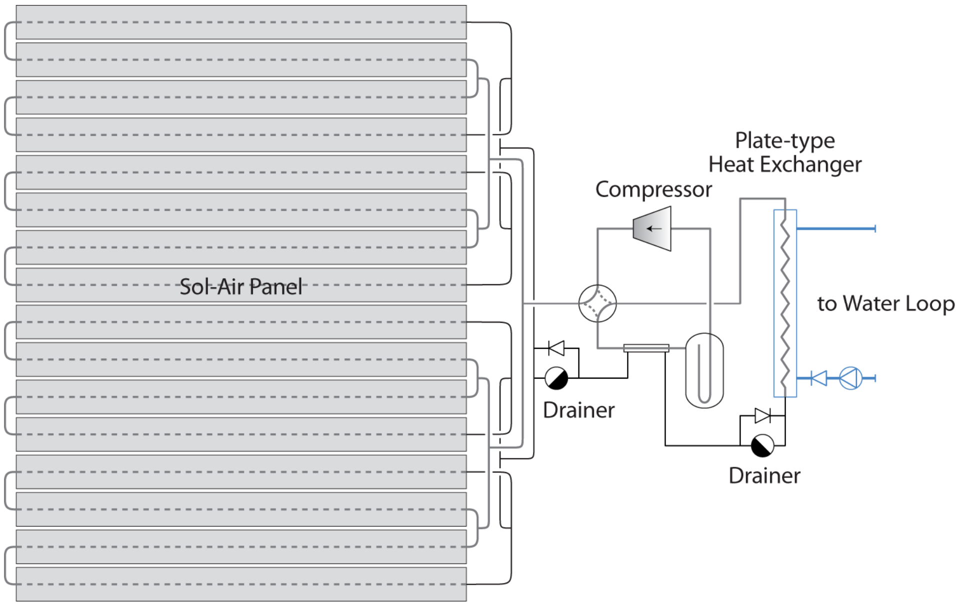

Figure 6: Refrigerant Circuit of SAHP Module

Nominal thermal power of the module is 5kW with the SA panel area of 7 square meters. Two SAHP modules are set on the penthouse roof of the building as shown in Figure 2. The specifications of the SAHP equipment are the followings:

- The SA panels are inclined 30 degrees facing south.
- Total SA panel area is 14 square meters.
- Nominal thermal output is 10kW in the heating and cooling cycle.
- Silicone monocrystaline solar cells are used and their total peak output is 1.5kW.
- Refrigerant is HFC-407C.
- Each module has a hermetic rotary compressor.

3.2 Heating Results

Operational data in the heating cycle of one SAHP module are traced in Figure 7. It was a fine day and outdoor dry-bulb temperature was about 10ºC in the morning and around 20ºC in the afternoon. The SAHP started at 8 a.m., when the SA panel heated by insolation temporarily increased the collected heat.
When operating, the relationship between collected heat and insolation is similar to Figure 5. After sunset, the SAHP worked in the air-source mode and the collected heat decreased accordingly.
Infrared radiation showed interesting behavior. It was minus when the SAHP was stopping but it turned to plus when operating: meaning IR radiation was collected. The change of flow direction may be explained by the panel temperature relative to the sky temperature. Further research is required.

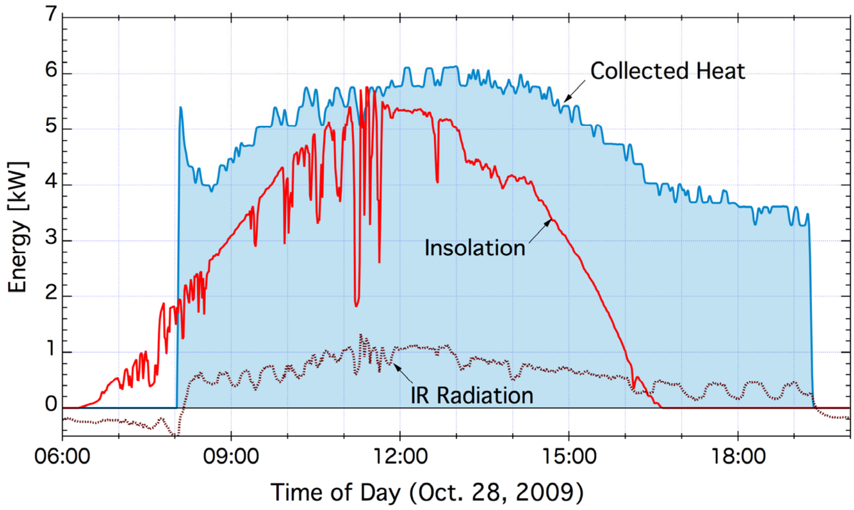

Figure 7: Collected Heat on a Sunny Day

Figure 8 shows COP that was obtained by dividing the heating output by the compressor input. The COP was higher when insolation was available. The photovoltaic generation barely surpassed the compressor input around noon.

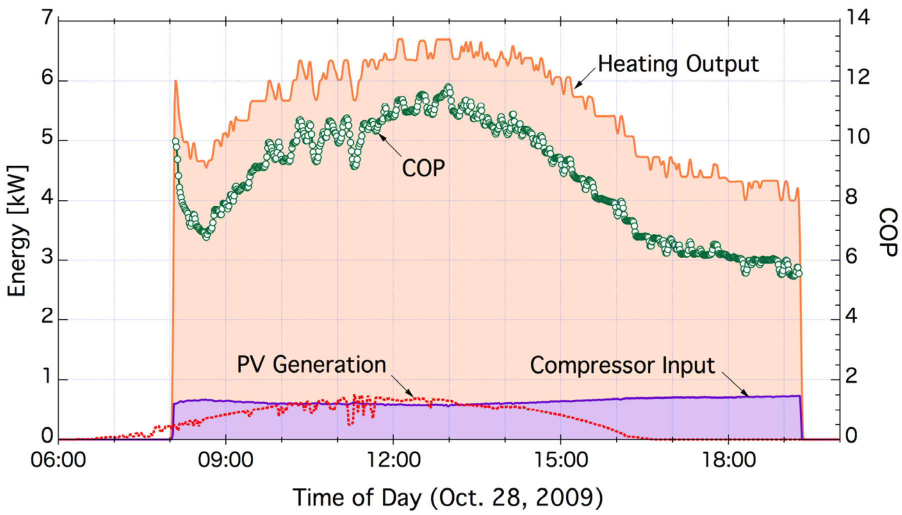

Figure 8: Heating Output and COP

3.3 Miscellaneous Results

Operational experiences through the heating season, from November 2009 to April 2010, are summarized as follows (Hino 2010):

- Frosting on the panel was observed on cold and humid days but defrosting was unnecessary.
- Collected heat by the SA panel constituted roughly half solar-source and half air-source on integration basis.
- Solar cells were effectively cooled by evaporating refrigerant when the SAHP was on and by air when it was off. Efficiency of the solar-cell module was about 15%.
- Solar energy utilization in both heat and power reduced CO_2 emission by 80 percent compared to a conventional gas boiler.

In the cooling cycle, the SAHP worked as a nocturnal radiator to cool water circulating to the underground tubes. Thus, soil temperature raised by waste heat of daytime air conditioning was lowered (i.e. restored) in the nighttime. The followings are the summaries:

- In the daytime, the SA panel was a photovoltaic power generator and supplied on-peak power to a grid while the SAHP itself consumed off-peak power from the grid.
- The solar cells were cooled by the backside fins and their temperature was kept no higher than 45ºC. The efficiency of the solar cell module was about 14 percent.
- Temperature of soil 0.2m distant from the underground tubes showed no rising tendency and it was maintained almost constant, between 20 and 21ºC throughout 2009 cooling season.
- Infrared radiation accounted for 20 to 30 percent of the total dissipated heat of the outdoor panel. IR radiation may help to alleviate a heat-island phenomenon to some extent.
- Rain effectively improved the heat dissipation capacity of the SA panel and the COP improved up to 10.

4 SYSTEM EXPANSION

Sky is the limit to the amount of solar and nocturnal radiation but they are available only intermittently. Air is trustier but its temperature changes widely and negatively correlates to the needs. Ground is more stable in temperature but extractable heat is limited. These merits and demerits of the various renewable energies will be supplemented each other and complementarily utilized by the proposed system named the Renewable Ground-Loop (ReGL) system as illustrated in Figure 9.

In the ReGL system, the water loop connects the SAHP modules, underground heat exchangers, and water-source heat pumps for various thermal demands, such as space heating, air conditioning, domestic hot water supply, and refrigerators. The circulating water will be maintained about 5K higher or lower than the natural ground temperature, about 17ºC at Tokyo area. Using this temperature for heat source and heat sink, heat pumps can effectively work in both heating and cooling cycles and COP of near 10 will be attainable if they are optimized to their ultimate objectives. Heat inputs and outputs around the water loop are explained in Figure 10.

Rejected heat of air conditioning and/or refrigeration heats the loop water while absorbing heat for space heat and/or hot water supply cools the loop water. This condition is called a waste heat recovery. If these input and output to the water loop are not equal amount or not simultaneous, the ground thermal storage manage them. Larger imbalance can be met by the SAHP.

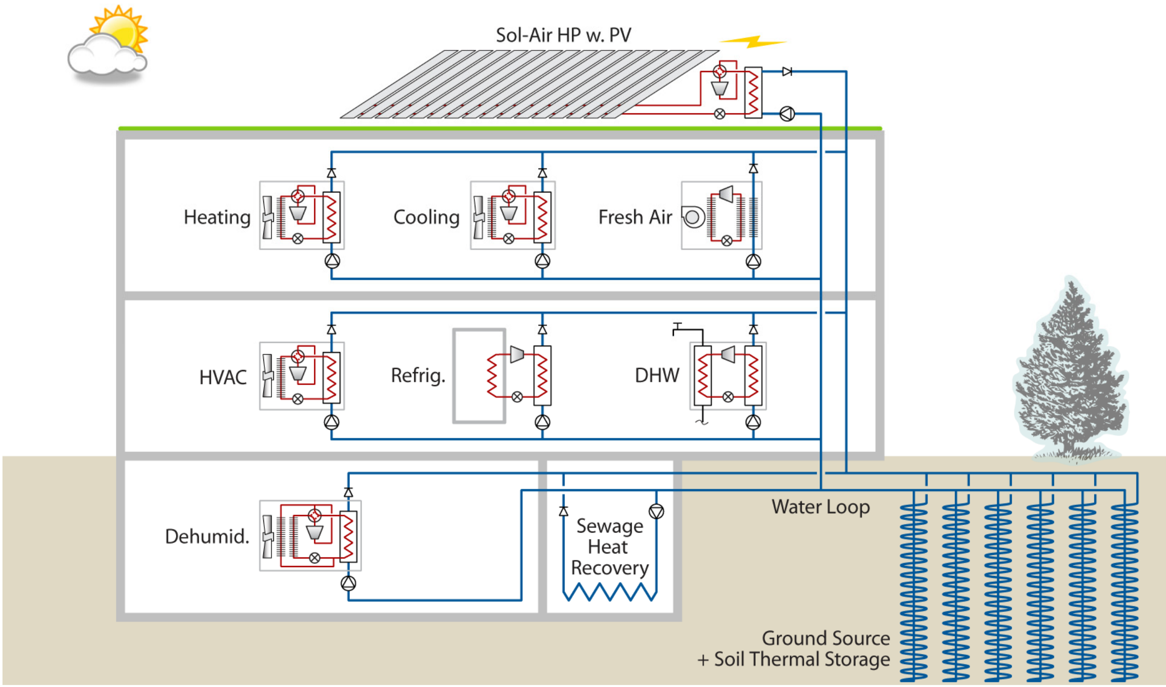

Figure 9: Scheme of Renewable Ground-Loop System

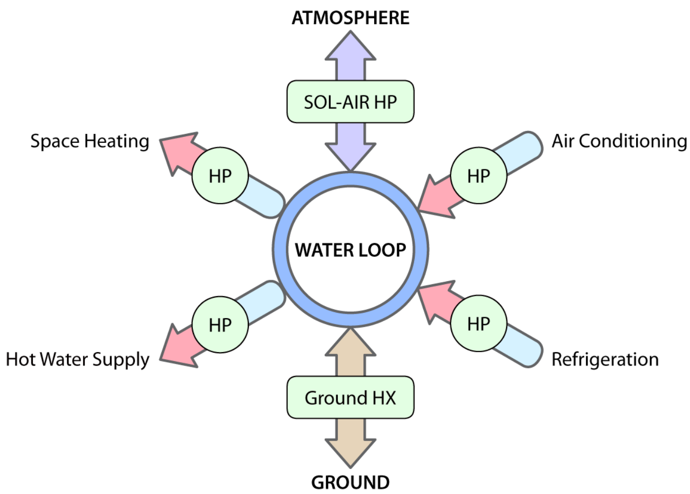

Figure 10: Heat Inputs and Outputs to Water Loop

5 CONCLUDING REMARKS

Although the SAHP can exploit various renewables, it is not a motley; rather, it is a simple technology that conforms to natural phenomena and the second law of thermodynamics.
The SAHP installed in 2009 has been servicing successfully and due improvements are in progress: a leading-edge refrigerant compressor can increase COP by more than 20%: avoid temperature glide in the SA panels caused by the zeotropic refrigerant: sprinkle water over the SA panel to work as an evaporative condenser when condensing pressure is high, etc. By implementing these schemes, power consumption of the SAHP may decrease substantially, and the photovoltaic power generation may exceed in the annual sum. Thus, net zero energy of the SAHP will be realized.
The SAHP is connected with the ground loop to integrate flow and stock of renewable energies. This water loop system named the ReGL will become a building thermal

infrastructure to which multiple heat pumps can be connected. The control of the ReGL system will be simple, or it can be more sophisticated, such as predicting weather conditions and/or adapting to a future smart grid.
Research and development of the ReGL system is underway in cooperation with the Institute of Industrial Science, the University of Tokyo with the subsidy from the Ministry of the Environment, Government of Japan.

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