

A DEVELOPMENT OF A HEAT PUMP FOR A THERMAL RECOVERY SYSTEM USING CO₂ AS A REFRIGERANT

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Abstract: This paper discusses the capacities of CO₂ as a refrigerant that recovers geothermal heat and waste heat from storage tanks. The CO₂ allows heat exchange through latent heat. Thus, it increases the exchanger duty per unit length of a heat collection pipe, which drastically reduces the heat pump installation cost and running cost. In this study, authors created pilot versions of an air conditioning system using geothermal heat and a cold and hot water production system using waste heat from a storage tank with CO₂. Authors evaluated their performance and electricity consumption. As a result, the air conditioning system showed about the same air conditioning abilities as a system with propylene glycol, which was installed for comparison when the installed length of the heat recovery pipe was one-third to one-half, and the electricity consumption was one-half with the CO₂. Meanwhile, the cold and hot water production system that used waste heat from a storage tank recovered as much as one to nine kilowatts of heat capacity per meter of a heat collection pipe when the CO₂ was used.

Key Words: Heat Pumps, Geothermal Recovery, CO₂, Latent Heat, Cost Reduction

1 INTRODUCTION

The heat pump technology has been attracting attention in recent years for its lower running cost and CO₂ emissions in comparison to systems that use fossil fuels. The demand for heat pumps for air conditioning, both heating and cooling, has been increasing in the field of protected horticulture because the inside of greenhouses needs to be kept at a constant temperature throughout the year depending on the crops produced. However, common heat pump systems use the air as a heat source; thus, they need to work under extremely large loads when they recover and release heat in cold regions where the temperature drops below zero and in extremely hot summer, like the summer in Japan in 2010, when the temperature rose above 40 °C. Thus, the load on the systems can be reduced if the heat is recovered underground where the temperature is relatively constant. In addition, the system releases the heat underground rather than into the air during cooling, which becomes an effective way of mitigating the heat island phenomenon. To recover geothermal heat, the system now exchanges heat through sensible heat by circulating the water refrigerant to which anti-freezing agent was added through pipe laid underground. Yet, the high initial cost for laying the pipe has been considered as one of the obstacles in promoting the system. When a system uses CO₂ refrigerant to recover geothermal heat, it means latent heat exchange, which increases the exchanger duty per unit space of laid pipes. This decreases

the diameter of geothermal heat pipes and shortens their lengths to produce the same performance; thus, the cost to lay pipes can be reduced. Also, if an already installed water storage tank, such as a rainwater tank and wastewater tank, is used as a heat source, it allows more efficient heat uses without spending large amounts for laying pipes. In this study, authors installed a 3.5 kW air conditioning system that recovers geothermal heat using CO₂ refrigerant in the office and evaluated its air conditioning performance and electricity consumption as an experiment. Authors also installed a system that recovers geothermal heat using propylene glycol solution as a comparison. In addition, authors created a pilot version of a 1.75 kW cold and hot water production system that recovers heat from a water storage tank using CO₂ refrigerant and studied its performance. As a result, the air conditioning system with the CO₂ refrigerant in the office showed the same level of air conditioning performance as the system with the propylene glycol solution when the installed length of the geothermal heat pipe was one-third to one-half, and the electricity consumption was one-half. In addition, authors found that the system delivered sufficient air conditioning effects even when the outer diameter of the geothermal heat pipe was reduced to $\phi 50$ and the pipe was coiled and laid at a shallow surface depth to reduce the initial cost. Authors also found that the cold and hot water production system that used the waste heat from a storage tank was able to recover as much as one to nine kilowatts of heat capacity per meter of heat-recovering pipe when it used CO₂ refrigerant. The next section describes the details of this experiment.

2 FEATURES OF THE CO₂ HEAT RECOVERY SYSTEM

Figure 1 shows the concept of the CO₂ heat recovery system. The left side of Figure 1 shows the geothermal heat pipe for CO₂ air conditioning for heating, the center the geothermal heat pipe for CO₂ air conditioning for cooling, and the right the conventional geothermal heat pipe that uses the propylene glycol solution. While the conventional geothermal heat pipe used polyethylene U-tubes, the CO₂ geothermal heat pipes used steel double-pipes with high rigidity. Conventional systems recover sensible heat, which is the equivalent of the temperature difference between input and output by circulating a propylene glycol solution as refrigerant and using the recovered heat for cooling and heating. Meanwhile, the CO₂ heat recovery system can increase the heat exchange capacity from the conventional method by using the latent heat of CO₂. During heating, CO₂ in the liquid phase enters the inner pipe of the geothermal heat pipe and evaporates in the ground as it recovers latent heat and then returns to the system in the gas phase through the outer pipe. During cooling, CO₂ in the gas phase enters the outer pipe of the geothermal heat pipe, condenses in the ground as it releases latent heat and then returns to the system in the liquid phase through the inner pipe.

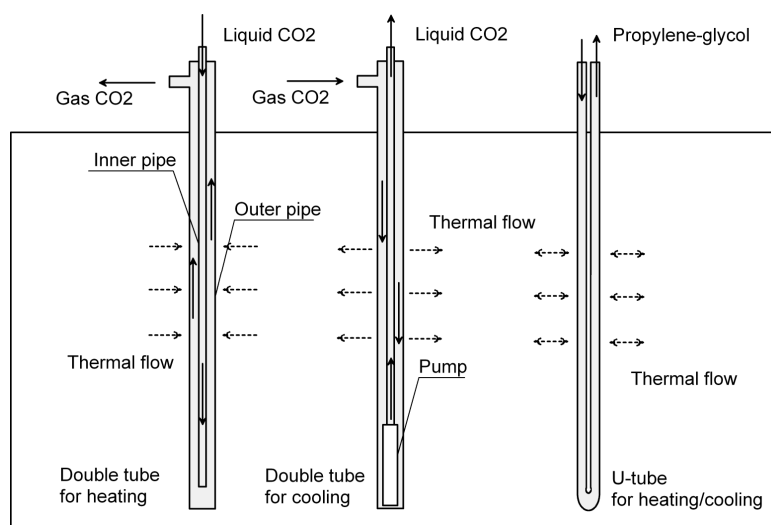


Figure 1: Concept of CO₂ thermal recovery system

3 METHOD OF THE EXPERIMENT

3.1 AIR CONDITIONING SYSTEM THAT USES GEOTHERMAL HEAT

Authors installed the experimental system shown in Figure 2 and Figure 3 to evaluate the air conditioning performance and electricity consumption of the CO₂ thermal recovery system. This air conditioning system uses geothermal heat as the heat source and runs hot water at 50 to 60 °C through the floor and cold water at 5 to 10 °C through the walls of the site office with a size of 6.3 m in length, 4.8 m in width, and 2.4 m in height. The system involves five geothermal heat pipes that use CO₂ as refrigerant, whereas four of them are used for heating and one for cooling. To compare with the conventional method, two geothermal heat recovery pipes that use propylene glycol solution as a refrigerant were installed. Switching the valve allowed the selection of which geothermal heat recovery pipes to use. Two types of 50-m-long geothermal heat pipes were used for heating with CO₂ refrigerant to study how the difference in the heat transfer surfaces would affect the performance: the outer diameter of the first type of double-pipe was $\phi 48.6$ mm; and the other type $\phi 89.1$ mm.

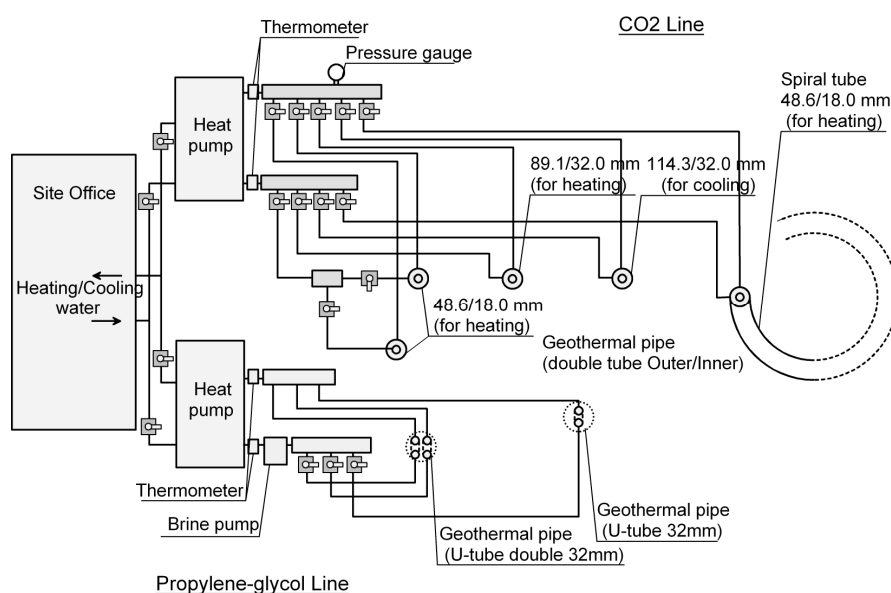


Figure 2: Air conditioning system that uses geothermal heat (plain view)

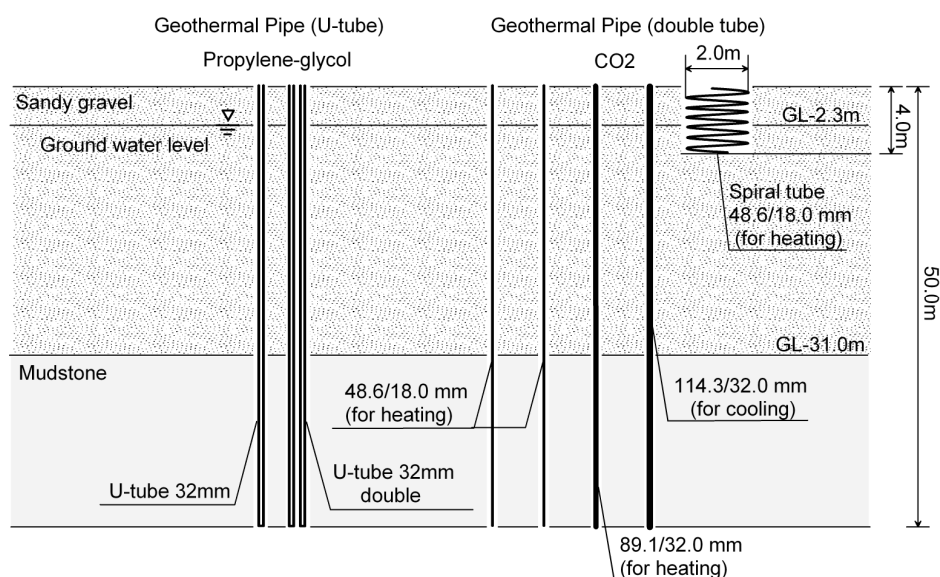


Figure 3: Air conditioning system that uses geothermal heat (sectional view)

Considering the size of the pump to be inserted, the outer diameter of the double-pipe for cooling was set at $\phi 114.3$ mm. In addition, geothermal heat-recovering pipes with $\phi 48.6$ mm in outer diameter, 40 m in length, and 4 m in underground depth were installed using spiral double-pipes that retain enough heat transfer surface even when the pipes are laid deeper in the ground. The performance of these pipes was then evaluated. This study used two types of geothermal heat-recovering pipes that used the conventional propylene glycol solution as refrigerant using a combination of single and double 50 m polyethylene U-tubes with $\phi 32$ mm in diameter. Using this experimental system, authors ran heating operation to keep the room temperature at 25 to 30 °C while the outdoor temperature was 5 °C and cooling operation to keep the room temperature at 25 to 27 °C while the outdoor temperature was 35 °C. Authors then studied cooling and heating capacities and electricity consumption with the geothermal heat-recovering pipes used in the experiment.

3.2 COLD AND HOT WATER PRODUCTION SYSTEM THAT USES WASTE HEAT

Authors installed an experimental system shown in Figure 4 to evaluate heating and cooling capacities and electricity consumption of a system that recovers waste heat from a water storage tank using CO₂ as refrigerant. This system heats or chills the water in a 200-liter tank using the heat recovered from the water storage tank. Three types of heat-recovering pipes were installed inside the 20 m³ water storage tank: vertical single-cylinder pipes with an outer diameter of $\phi 89.1$ mm and the length of 1.6 m, another vertical single-cylinder pipes with an outer diameter of $\phi 48.6$ mm and the length of 1.6 m, and spiral single-cylinder pipes with an outer diameter of $\phi 48.6$ mm, a total length of 6.7 m, and the height of 1.6 m. The tank was filled with the water at 27 °C. While hot water was being produced, the CO₂ refrigerant in a liquid phase entered the heat-recovering pipe from the bottom side of the water storage tank, raised up inside the pipe as it evaporated, and returned to the heat pump in a gas phase. While cold water was being produced, the CO₂ refrigerant in a gas phase entered the heat-recovering pipe from the upper part of the water storage tank, descended through the pipe as it condensed, remained in the reserve tank in a liquid phase, and returned to the heat pump with the assistance of the pump. Heating and cooling capacities and electricity consumption of individual heat-recovering pipes were studied in this experiment by heating or chilling the water with the initial temperature of 18 °C for one hour.

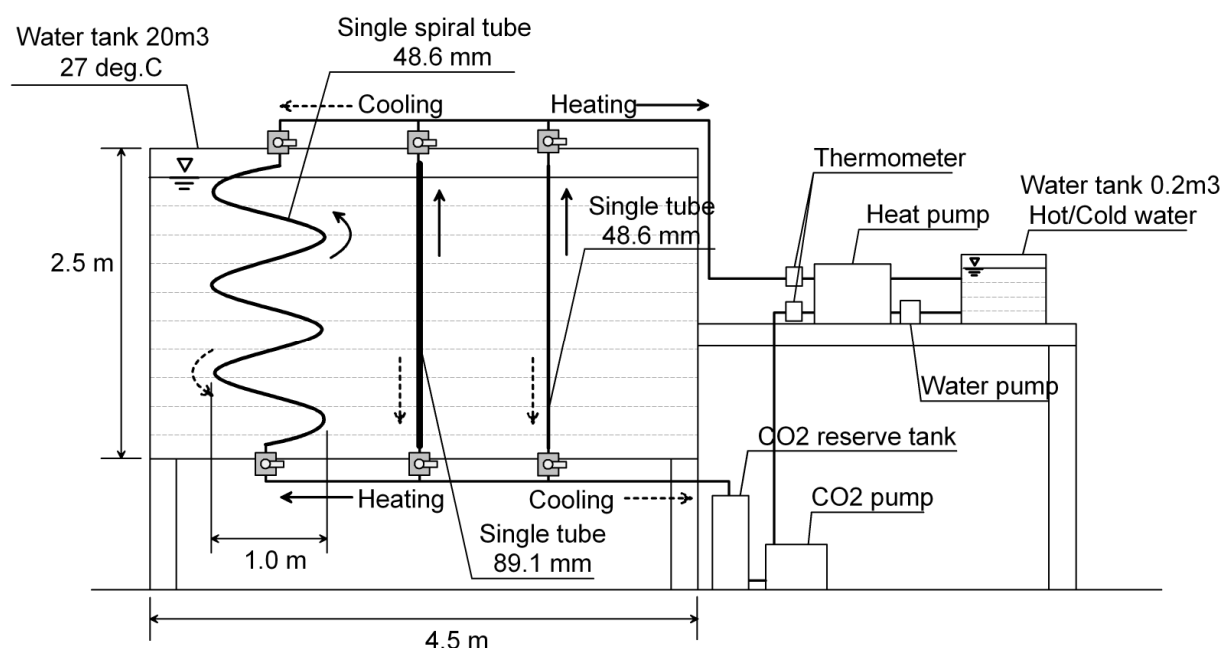


Figure 4: Cold or hot water production system that uses waste heat

4 OUTCOMES OF THE EXPERIMENT

4.1 AIR CONDITIONING SYSTEM THAT USES GEOTHERMAL HEAT

Table 1 and Table 2 show outcomes of the heating experiment and cooling experiment, respectively. In the heating experiment, the system was able to deliver enough performance for heating except when it used double-layer geothermal heat recovery pipes with an outer diameter of $\phi 48.6$ mm and a total length of 50 m. It reduced the electricity consumption to half and more than doubled the COP value in comparison to the outcome of the heating experiment using the system that used the conventional propylene glycol solution as refrigerant. One of the factors was that the new system did not require a pump to circulate the refrigerant because the CO₂ refrigerant exchanged heat using natural circulation. A total length of the geothermal heat recovery pipe was able to reduce to one-half when the system used the double-pipe with an outer diameter of $\phi 89.1$ mm and a length of 50 m and the spiral double-pipe with an outer diameter of $\phi 48.6$ mm and a length of 40 m. The system also delivered enough performance for cooling while reducing electricity consumption and increasing the COP compared to the conventional system in the cooling experiment. The total length of the geothermal heat recovery pipe was reduced to one-third of the conventional system.

Table 1: Outcome of the air conditioning system (heating operation) which used geothermal heat

Heat transfer fluid	The type of geothermal pipe	Heating ability	Electric consumption	COP
CO ₂	Double tube $\phi 89.1$ L:50m	5.6 kW	2.6 kW	2.2
	Double tube $\phi 48.6$ L:50m $\times$ 2	5.0 kW	2.2 kW	2.5
	Double tube $\phi 48.6$ L:50m	2.4 kW	1.9 kW	1.3
	Double tube spiral $\phi 48.6$ L:40m(Depth:4m)	4.2 kW	2.0 kW	2.1
Propylene-glycol	U-tube(Single) $\phi 32.0$ L:50m $\times$ 2	4.6 kW	4.2 kW	1.1

Table 2: Outcome of the air conditioning system (cooling operation) that used geothermal heat

Heat transfer fluid	The type of geothermal pipe	Cooling ability	Electric consumption	COP
CO ₂	Double tube $\phi 114.3$ L:50m	4.2 kW	1.9 kW	2.6
Propylene-glycol	U-tube (Single + Double) $\phi 32.0$ L:50m $\times$ 3	4.4 kW	2.8 kW	1.6

4.2 COLD AND HOT WATER PRODUCTION SYSTEM THAT USES WASTE HEAT

Table 3 and Table 4 show the outcomes of the heating experiment and cooling experiment, respectively. The water temperature inside a 20 m³ water storage tank was 27 °C. The temperature change of the 200 L water during one-hour experiments was 15 to 25 °C. The filled amount of CO₂ was also used as one of the parameters of the experiment. The highest heating performance was observed when the system used a vertical pipe with an outer diameter of $\phi 48.6$ mm and a total length of 1.6 m, and 8.5 kg of CO₂ was filled. The next highest performance was observed with the spiral pipe with an outer diameter of $\phi 48.6$ mm

and a total length of 6.7 m, and 12.4 kg of the filled CO₂. The third highest performance was observed with the vertical pipe with an outer diameter of $\phi 89.1$ mm and a total length of 1.6 m and 18.5 kg of the filled CO₂. In terms of the amount of CO₂ filled, the heating performance increased as more CO₂ was filled when the system used vertical pipe with a large diameter of $\phi 89.1$ mm. Meanwhile, the heating performance decreased if the amount of the filled CO₂ became larger than a certain level when the system used a vertical pipe and spiral pipe with a small diameter of $\phi 48.6$ mm. In the cooling experiment, the highest cooling performance was observed when the system used a vertical pipe with an outer diameter of $\phi 89.1$ mm and a total length of 1.6 m and 8.2 kg of the filled CO₂. The next highest performance was observed with a spiral pipe with an outer diameter of $\phi 48.6$ mm and a total length of 6.7 m and 12.2 kg of the filled CO₂. In terms of the amount of CO₂ filled during cooling operation, the cooling performance increased as the amount of the filled CO₂ increased in both the vertical pipe with an outer diameter of $\phi 89.1$ mm and a spiral pipe with an outer diameter of $\phi 48.6$ mm.

Table 3: Outcome of the cold and hot water production system (heating operation) that used waste heat

Type of thermal pipe	Amount of CO ₂	Heating ability	Electric consumption	COP
Single tube $\phi 89.1$ L:1.6 m	6.8 kg	2.6 kW	1.6 kW	1.6
	10.8 kg	3.4 kW	1.5 kW	2.3
	18.5 kg	3.6 kW	1.8 kW	2.0
Single tube $\phi 48.6$ L:1.6 m	4.8 kg	2.8 kW	1.4 kW	2.0
	8.5 kg	6.4 kW	1.6 kW	4.0
	13.3 kg	3.3 kW	2.0 kW	1.7
Single tube spiral $\phi 48.6$ L:6.7 m	12.4 kg	4.9 kW	2.2 kW	2.2
	20.2 kg	3.4 kW	2.2 kW	1.5

Table 4: Outcome of the cold and hot water production system (cooling operation) that used waste heat

Type of thermal pipe	Amount of CO ₂	Cooling ability	Electric consumption	COP
Single tube $\phi 89.1$ L:1.6m	6.8 kg	4.8 kW	2.2 kW	2.2
	8.2 kg	15.0 kW	2.0 kW	7.5
Single tube spiral $\phi 48.6$ L:6.7m	8.7 kg	4.8 kW	2.0 kW	2.4
	10.0 kg	5.0 kW	2.1 kW	2.4
	12.2 kg	7.4 kW	2.2 kW	3.7

5 OBSERVATION

5.1 AIR CONDITIONING SYSTEM THAT USED GEOTHERMAL HEAT

Figure 5 shows the temperature change in the CO₂ refrigerant at the entrance and the exit of geothermal heat recovery pipe when the system ran heating operation using a geothermal heat recovery pipe with an outer diameter of $\phi 89.1$ mm and a total length of 50 m. The CO₂ refrigerant entered the geothermal heat recovery pipe in a liquid phase and returned to it in a gas phase during heating operation. The temperature remained almost constant at about 4°C during this process, which indicated that the heat exchange was conducted only through the latent heat of the CO₂. A large temperature difference was observed when the needed heating performance was not observed using the geothermal heat recovery pipe of the outer diameter of $\phi 48.6$ mm and a total length of 50 m; the temperature of the CO₂ refrigerant was 0 °C at the entrance and 13 °C at the exit. This is probably because an insufficient amount of

CO₂ evaporated in the geothermal heat recovery pipe, which caused the pressure to drop, prevented the CO₂ from rising to the surface, and made the amount of CO₂ in circulation insufficient. Figure 6 shows the temperature change in the CO₂ refrigerant at the entrance and exit of the geothermal heat recovery pipe when the system ran cooling operation using the geothermal heat recovery pipe with an outer diameter of $\phi 114.3$ mm and a total length of 50 m. It shows that the temperature at the entrance and the exit were about the same and remained constant at 27 °C. The system delivered necessary heating performance in the experiment that used the spiral geothermal heat recovery pipe with an outer diameter of $\phi 48.6$ mm, a total length of 40 m, and laying depth of 4 m even though the total length of the pipe was shorter and the heat transfer surface was smaller than the vertical geothermal heat recovery pipe.

The system was able to retain the necessary amount of CO₂ in circulation during heating because of the shallow laying depth of 4 m, which allowed the CO₂ gas to rise up through the pipe even under low pressure. The flow style of CO₂ gas inside a spiral pipe is now being studied.

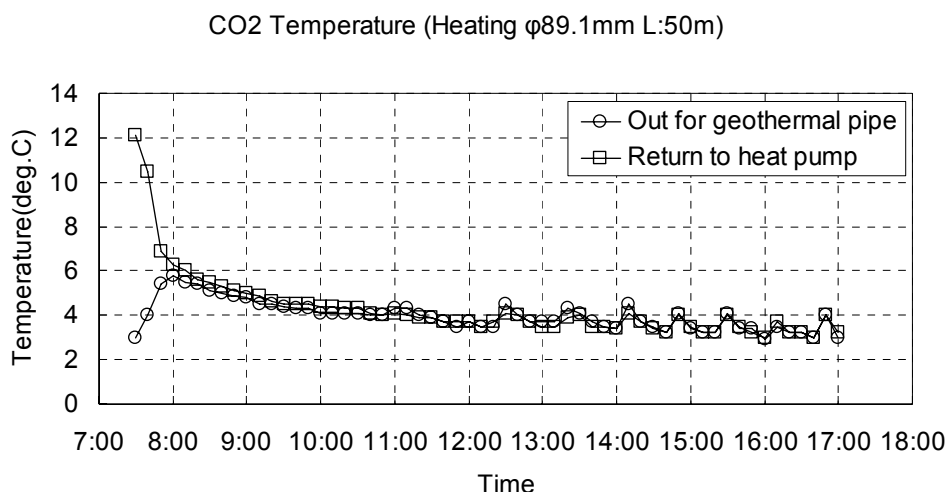


Figure 5: CO₂ refrigerant temperature during heating operation

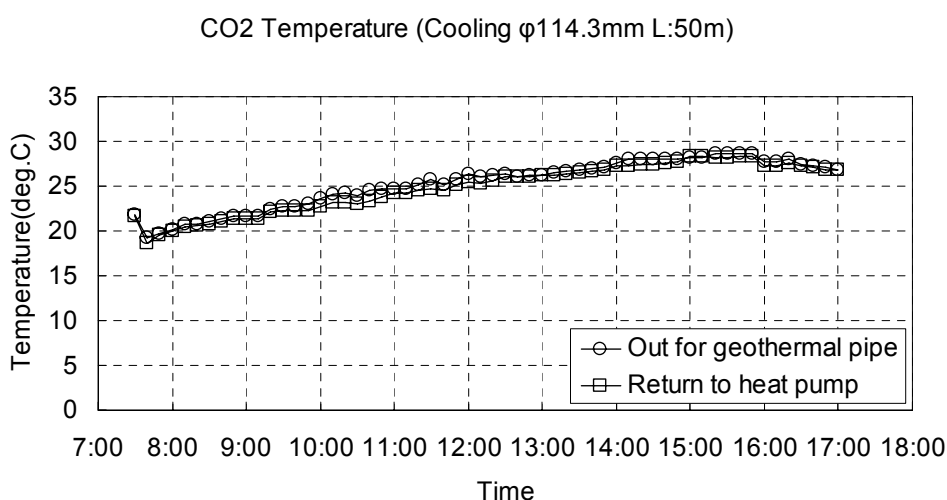


Figure 6: CO₂ refrigerant temperature during cooling operation

5.2 COLD AND HOT WATER PRODUCTION SYSTEM THAT USES WASTE HEAT

The temperature of the CO₂ refrigerant was higher than when the system used geothermal heat because the temperature of the water inside the water storage tank, which was used as the heat source, was high at 27 °C. The effect of the pipe diameter was small during the heating operation. This was probably because the latent heat that was available for heat exchange decreased, since the temperature of the CO₂ refrigerant exceeded 30 °C and became closer to the limit when the system used the heat recovery pipe of the outer radius of $\phi 89.1$ mm. When the system used a heat recovery pipe of $\phi 48.6$ mm in diameter, the temperature of the CO₂ refrigerant did not exceed 30 °C as shown in Figure 7. Yet, liquid accumulated inside the heat recovery pipe when the filled amount of CO₂ exceeded a certain level and caused the amount of CO₂ in circulation to decrease and lowered the heating performance. As shown in Figure 8, the CO₂ refrigerant circulated during cooling operation at a near-critical state. Unlike the heating operation, the cooling performance improved as more CO₂ was filled without making the amount in circulation insufficient because the CO₂ was forced-fed to the system with a liquid transfer pump. Table 5 shows thermal properties of CO₂ and Figure 9 the phase diagram of CO₂.

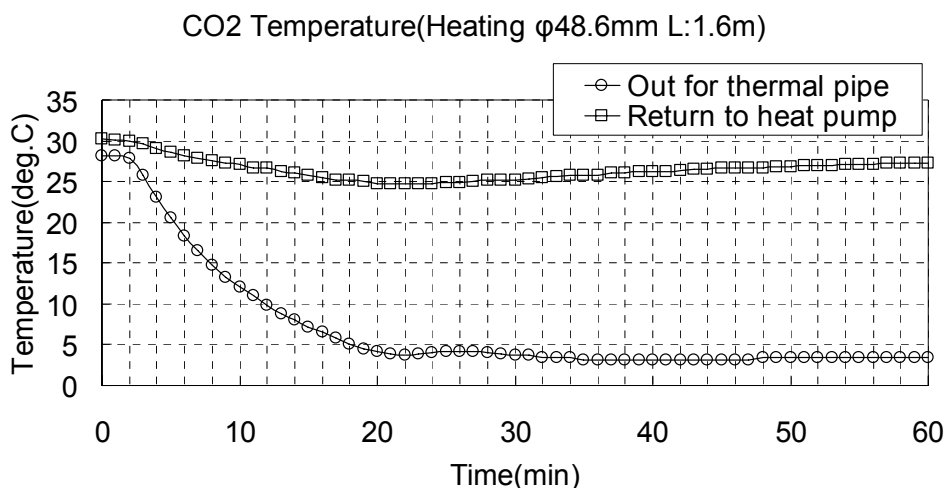


Figure 7: CO₂ refrigerant temperature during heating operation

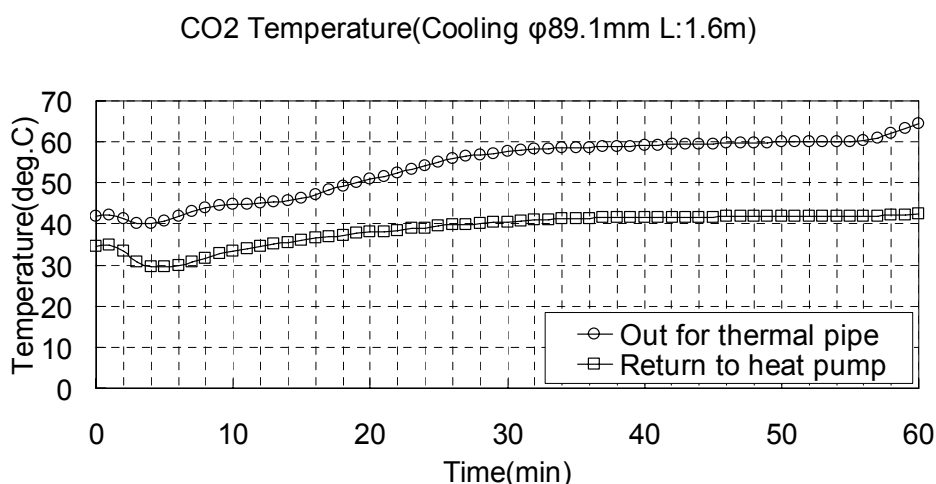


Figure 8: CO₂ refrigerant temperature during cooling operation

Table 5: Thermal properties of CO₂

Temp. deg. C	Pressure MPa abs	Density		Latent heat kJ/kg
		Liquid kg/L	Gas kg/m ³	
-5	3.045	0.9538	82.4	249.12
0	3.485	0.9248	96.3	235.01
5	3.972	0.8931	113.0	219.18
10	4.506	0.8580	133.0	201.35
15	5.093	0.8179	158.0	180.32
20	5.733	0.7707	190.2	155.33
25	6.432	0.7058	240.0	119.45
30	7.192	0.5964	334.4	63.01
31	7.351	0.4639	463.9	0.00

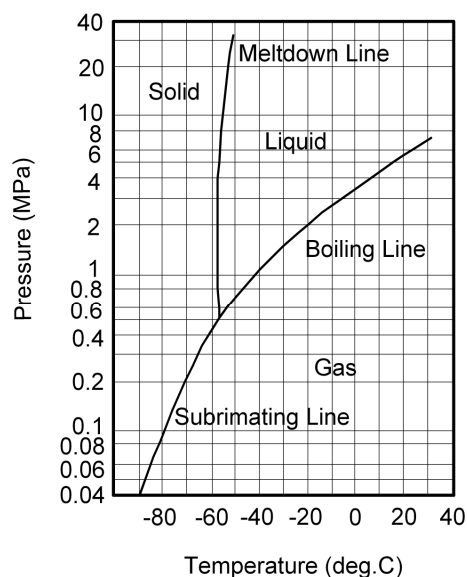


Figure 9: CO₂ phase diagram

6 CONCLUSION

This paper discussed the heat pump system that uses CO₂ refrigerant and efficiently recovers heat from stable heat sources, such as underground and water storage tanks. The comparison with the system that exchanged heat through sensible heat using the conventional anti-freezer revealed that both running cost and initial cost could be reduced. Decreasing the diameter and length of pipes to be laid in the ground or using spiral pipes and to lay them at a shallow depth in the ground are possible by CO₂. To bring out the maximum capacity of the system, the volume of heat recovery pipes and the amount of CO₂ to be filled must be adjusted to optimal conditions while paying attention to the condition of the heat sources. However, this study was able to use 112 W/m of heat at most (46 W/m with the conventional method) when it used geothermal heat and 9.4 kW/m of heat at most when it used waste heat from a water storage tank. This system will be widely applicable in many fields as a technology to promote the use of natural energy in the form of geothermal heat and the reuse of waste heat, as well as to reduce the environmental burden.

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8 REFERENCES

- Satoko Taniguchi, and Masakazu Ohtake, 2009, "Abstract of a utilizing geothermal system and the effect of application for greenhouse," *Greenhouse Horticulture*, Vol.146, pp.26-31.
- Satomi Okushima, "The water-source heat pump potential in agricultural area," *Agricultural area study forum* 2010, pp.39-44.
- JIMGA 2009, "JIMGA liquid carbon dioxide text book," Japan Industrial and Medical Gases Association, pp.3.