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FREEZE PROTECTION METHOD USING HOT WATER FOR PASSIVE SOLAR WATER HEATING SYSTEM

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In the present work, a new freeze protection method is introduced with intended applications for passive solar water heaters. Though electro-thermal wire heat tracing is popularly used to prevent freezing with subsequent risk of burst, this approach is problematic due to resistance heater failure and excessive electric power consumption. In the experimental device, hot water in thermal storage tank is used to heat the outlet pipe from the tank when the surface temperature of the pipe falls lower than a pre-determined set point. The cold water pipe to the thermal storage tank is installed in direct contact with the hot water pipe, controlling its temperature by conduction with the hot water pipe.

Keywords: Solar energy; freeze protection; natural circulation; hot water tracing technique.

Nomenclature

C_p : Specific heat, kJ/kg · K
k : Thermal conductivity, W/m · K
h_o : Convective heat transfer coefficient, W/m^2 · K
L : Length of pipe, m
r_i : Inner radius of pipe, m
r_o : Outer radius of pipe, m
r_{ad} : Outer radius of insulator, m
t : Time, s
t_f : Elapsed time till final temperature, s
T : Temperature of water, °C
T_i : Initial temperature of water, °C
T_f : Final temperature of water, °C
T_o : Outdoor temperature, °C
$T_{P,H}$: Surface temperature of hot water pipe, °C
$T_{P,L}$: Surface temperature of cold water pipe, °C
$T_{s,\mathrm{out}}$: Exit temperature of storage tank, °C
U : Overall heat transfer coefficient, W/m^2 · K

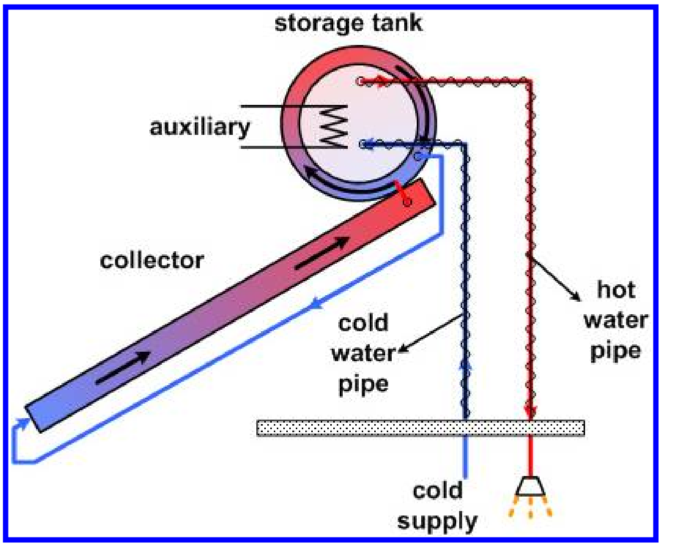


Fig. 1. Schematic diagram of general passive water heater.

1. Introduction

Two typical solar water heating systems are natural-circulation (passive) type, which is inexpensive but easily influenced by the weather, and the forced circulation (active) type, which is less likely to freeze but has a comparatively complex structure. The advantage of the natural-circulation solar water heating system is its simplicity and efficiency due to absence of a circulation pump and control devices.[1] The most commonly used thermal storage tank for the passive solar water heater is tank-in-tank type due to its efficiency and simple manufacture processes.[2] As shown in Fig. 1, anti-freeze solution heated in the collector circulates through the jacket to heat water inside the tank then, the solution naturally circulates back to the collector when the temperature falls.

Circulation of anti-freeze solution prevents freezing of collectors, jacket of the storage tank and their connecting pipes; however, cold and hot pipes filled with water are likely to freeze and burst when the atmospheric temperature falls below 0°C. To solve this problem, "hot wire tracing method" has been suggested which involves wrapping electric resistance heating wires around the pipes to heat the pipes during periods of cold temperatures. However, frequent operations of the wires during winter seasons result in the failure of the resistance heating elements and high electricity bills. Another method, "hot water tracing method" has not been applied in the passive solar water heater because it could heat the hot water pipe with hot water from the storage tank but not the cold water pipe.[3] Additionally, a method of removing water in pipes and storage tank could be considered, but it was difficult to completely remove lots of water enduring waste. Also very small amount of residual water in pipes can lead to a burst by freeze.

Presented here is a method that suggests "combined-pipes hot water tracing method" to prevent freezing by using hot water in the storage tank. In this method, cold and hot water pipes are adjacently placed and insulated as shown in Fig. 2. A similar principle can be observed in the feet of penguins. Blood vessels running to and from the feet of penguins are organized to facilitate countercurrent heat exchange. Arteries carrying warm blood toward the feet run alongside veins carrying cool blood up from the feet.[4]

A temperature controller detects the surface temperature of the hot water pipe and automatically

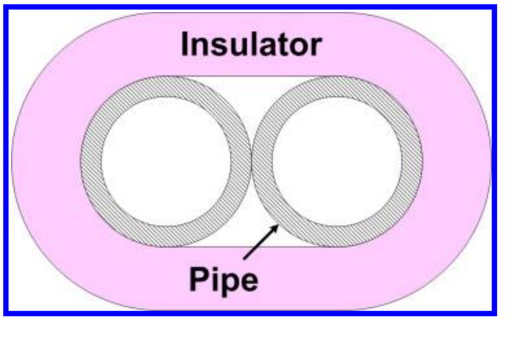


Fig. 2. Combined pipes.

opens a valve to release hot water from the storage tank to the outside in order to heat the hot water pipe up to a certain degree. Then the heated hot water pipe heats slowly the adjacent cold water pipe.

2. Cooling Behavior in Pipes

By experiment and calculation, we obtained the rate of heat transfer between the hot and cold pipes in order to assess the efficacy of this method for freeze protection. The assessment includes estimates of the energy consumption in hot water tracing method and operating frequency. Although factors affecting cooling rate of water in pipe include pipe diameter, insulation thickness, ambient temperature, wind speed and initial water temperature, this experiment took into account of the first three factors mainly.

Carbon steel pipes of 15 A (internal diameter 16.1 mm and thickness 2.8 mm) and 20 A (internal diameter 23 mm and thickness 2 mm) 30 cm in length were 90% filled with water, insulated and vertically placed in a freezer. The freezer in the experiment was set to maintain 3 m/s wind speed within ± 0.3°C of a set temperature.

Numerical analyses of the heat transfer problem were developed by using a commercial code STAR-CD. The computational grids of $146 \times 1 \times 300$ were found to be reasonable for resolving complicated flow patterns employing the PISO algorithm and the two-equation model $\kappa - \varepsilon$. Under the same condition in Fig. 3, the elapsed time from 12.5°C to 0°C is 1.3 h both in experiment and in simulation for 20 mm insulation, and 1.7 h in experiment and 1.8 h in simulation for 40 mm insulation. Although both of the results are in good agreement, the numerical simulations are highly time-consuming and computationally intensive. For the 2-h simulation with time step of 2 s, the computation time is typically about 9 h on Intel® CoreTM2 Quad 2.66 GHz.

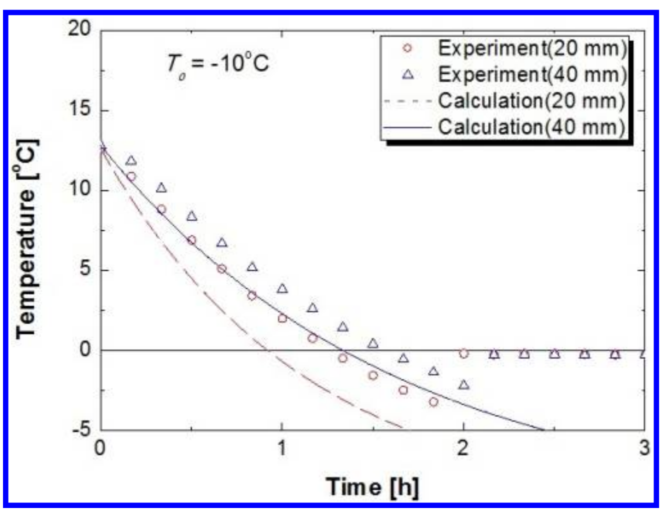


Fig. 3. Timewise variation of water temperature according to insulation thickness.

The purpose of the calculation in the present research is to understand a rough trend for cooling behavior of water in pipe, so the lumped system analysis other than the above precise simulation was applied disregarding influences by convection and temperature distribution for simplicity. Overall heat transfer coefficient U, temperature T and elapsed time till reaching final temperature t_f are arranged in the following equations

$$\frac{1}{UA_i} = \frac{\ln(r_o/r_i)}{2\pi L k_{\text{pipe}}} + \frac{\ln(r_{ad}/r_o)}{2\pi L k_{ad}} + \frac{1}{2\pi r_{ad} L h_o}, \quad (1)$$

$$\frac{T - T_o}{T_i - T_o} = \exp\left(-\frac{2Ut}{r_i \rho C_p}\right), \quad (2)$$

$$t_f = -\ln(T_f - T_o)\frac{r_i \rho C_p}{2U}, \quad (3)$$

where T_i and T_f are the initial and final temperatures of the water in pipe and T_0 is the ambient temperature.

Figure 3 compares temporal variation of water temperature when using 20 mm and 40 mm polyethylene insulation (thermal conductivity 0.037 W/m · K) on 15 A pipes. The initial water temperature in pipes was 12.5°C and the freezer temperature was maintained at -10°C. The estimated value of elapsed time to reach 0°C was 25% less than the experimental value, which was thought to be appropriate for the purpose of the analysis in spite of somewhat large difference compared to the strict simulation.

Figure 4 shows the elapsed time to 0°C according to insulation thickness. The rate of change of water temperature is twice as long in pipe 20 A compared to 15 A. For a 15 A pipe, water temperature duration time increases by 50% when the 40 mm thick insulator is used instead of 20 mm. The longer duration time saves energy used for heating the water, so it is recommended to use 40 mm thick insulator which is well applied outside to prevent better burst by freeze and to save energy. Despite the advantages, 20 mm thick insulator was used in the experiment to simulate a harsher condition.

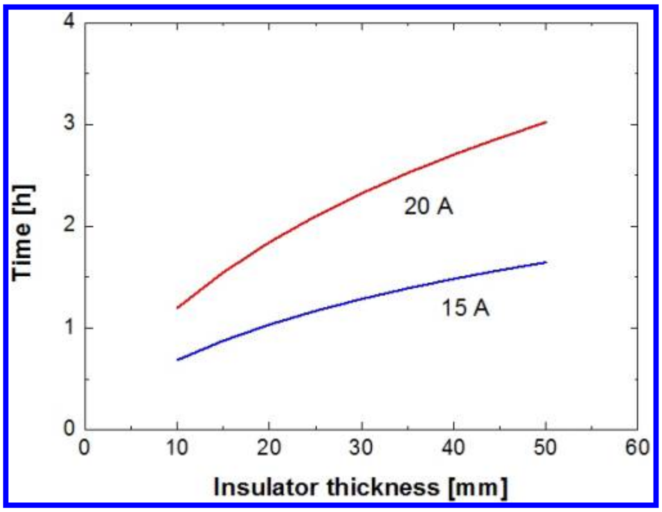


Fig. 4. Elapsed time to 0°C according to insulation thickness ($T_i = 15$°C, $T_o = -10$°C, $V_o = 2$ m/s).

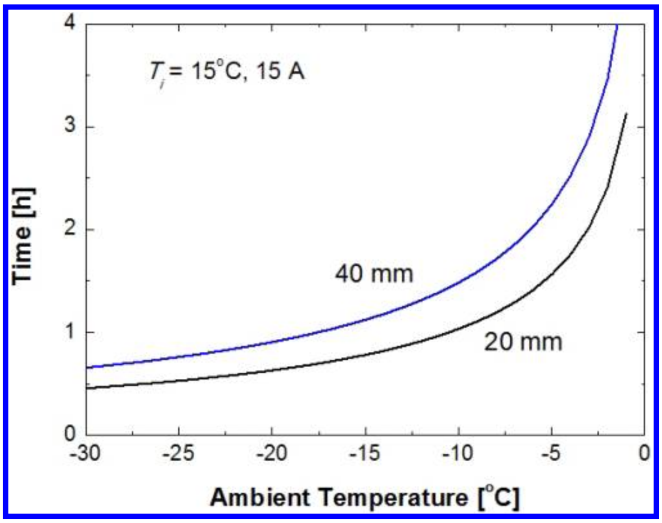


Fig. 6. Elapsed time to 0°C according to ambient temperature.

Figure 5 shows the effect of initial water temperature in pipes. Although high initial water temperature increases the duration time, the effect is diminished as the water temperature is raised higher. Therefore, if a hot wire is used to heat the water in pipes, it is advantageous to frequently heat the water up to a low degree rather than occasionally to a high degree. Controlling to a lower temperature when using heat tracing increases operating frequency of the resistance heating elements; thereby, leading to a greater rate of deterioration due to cycling. Figure 6 compares 20 mm and 40 mm thick insulator in different ambient temperatures. Although wind speed has little influence on the duration time, the ambient temperature has a great influence like Fig. 6, which is shown by the duration dramatically increasing in ambient temperature higher than −10°C.

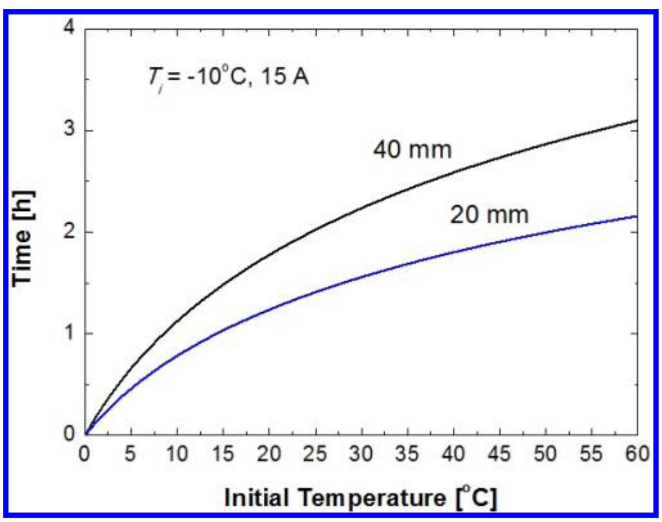


Fig. 5. Elapsed time to 0°C according to initial water temperature.

On the other hand, a simple test in the freezer was tried to measure electric power consumption of hot wire tracing method for 12 h in −10°C ambient temperature. The hot wire heats the water when its temperature drops to 2°C and stops heating when it reaches 10°C. The experiment resulted in the electric power consumption of 0.05 kWh/m.

Now it is necessary to focus a heat transfer behavior of combined piping, the core of the new method proposed by this research to prevent burst by freeze in passive solar water heater. The pipes are placed next to each other like Fig. 2 rather than adjoining them by welding. Figure 7 shows temporal variation of water temperature in combined pipes when two pipes with initial temperatures of 22°C and 40°C, respectively, are rapidly joined and vertically placed in a −5°C freezer. As expected, the temperature of the hot pipe quickly falls as it transfers heat to the cold pipe. The cold pipe increases slightly at first and then slowly decreases in temperature along with the hot pipe. The temperature gaps of the two pipes become eventually narrow and the two pipes almost simultaneously approach 0°C. The experiment also showed that 40 mm thick insulator has 1.5 times longer duration time than 20 mm thick insulator.

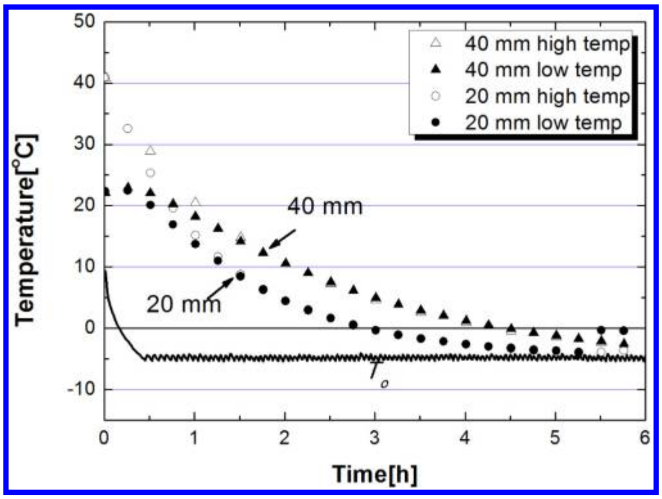


Fig. 7. Timewise variation of water temperature in combined pipes.

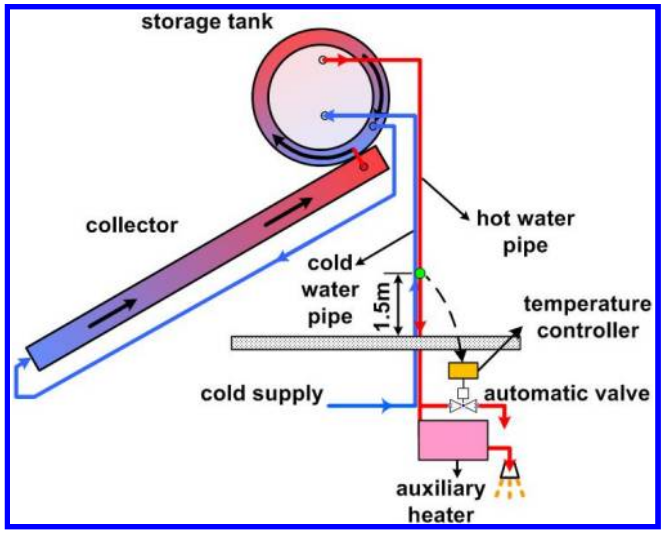


Fig. 8. Schematic diagram of solar water heater with combined pipes and automatic valve.

3. System Setups and Experiments

For the main experiment, solar water heating system consisted of a collector and a thermal storage tank was placed facing south in Korea. Table 1 shows the specification of the system. 30 wt.% propylene glycol solution is used as a heating fluid circulating through the collector and the thermal storage tank. The heating fluid absorbing energy in the thermal collector is circulated to the thermal storage tank installed above the collector via natural convection. The stored thermal energy is then heat exchanged with the water inside the storage tank to produce usable hot water. When hot water is supplied to the load, pipes were designed to provide cold water to bottom of the tank and to discharge hot water from top of the tank.

Figure 8 shows a schematic of automatic valve (electric power consumption 3 W) on hot water pipe 11 m in length and piping together with a main experimental body. A thermocouple was attached at the coldest part of hot water pipe in order to control the automatic valve or the hot wire, which was set to turn on and off by a temperature controller. Electronic wattmeter was used to measure hot wire electric power consumption. Temperatures on pipes and storage tank were read at each measuring point every 3 or 36 s.

Table 1. Specification of system.

Collector	Size	1937 mm × 1022 mm
	Area	1.99 m^2
	Slope	40°
Storage tank	Type	tank in tank
	Capacity	150 L
Pipe	Material	carbon steel
	Diameter	15 mm
Heating wire	Resistance	16 W/m

The experiment was conducted during winter seasons from December of 2009 to February of 2012. When the pipe temperature at control point drops below the lower setting value, the automatic valve of Fig. 8 opens to release hot water from the storage tank; simultaneously, cold water flows in due to city water pressure. The automatic valve closes when the water temperature reaches the upper setting value. However, the complete open or close of the valve takes 30 s, so the hot water continues to discharge after reaching the upper setting value and raises the pipe temperature more. Therefore, the upper setting value was set as 10°C considering the effect of extra hot water discharge. On the contrary, although it is desirable to set the lower setting value near 0°C, it was set as 2°C considering temperature nonuniformity in pipe and measurement errors in the temperature controller.

It is important that the temperature sensor for control is not installed on the cold pipe because the cold pipe temperature reaches the upper setting value at a slow rate and the hot water discharge greatly increases. The temperature of the hot pipe is lowest at a point right before entering the indoors. It is because hot water from the storage tank first heats the pipe area in proximity to the tank and lastly heats the pipe area distal from the tank. Considering these factors, the temperature sensor was placed on the hot water pipe at 1 m before indoor entry to minimize influence from the indoor environment.

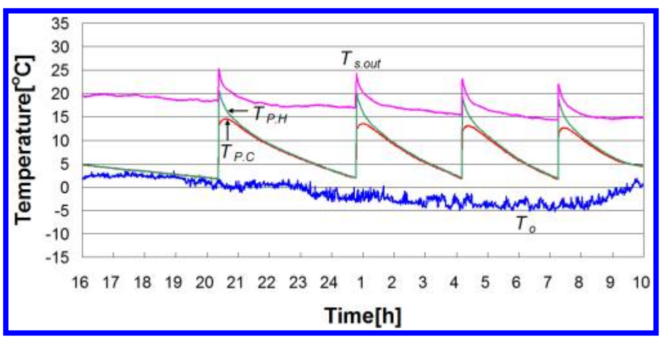
4. Results and Discussion

Figure 9 is a result graph of hot water tracing method. Figure 9(a) shows activation of freeze prevention system when the ambient temperature falls near −5°C. The surface temperatures of hot and cold water pipes rose up to 20°C and 15°C, respectively, and maintained above the lower setting value 2°C for 5 h. But the duration is clearly decreasing as the ambient temperature decreases. The experiment revealed that 3 L of hot water was discharged when freeze prevention system was activated. The amount of 25% more water was discharged considering that hot water pipe volume is 2.3 L. The extra water was used to heat carbon steel pipes. Therefore, 0.27 L hot water was discharged per 1 m of 15 A steel pipe when the water temperature in thermal storage tank was 25°C.

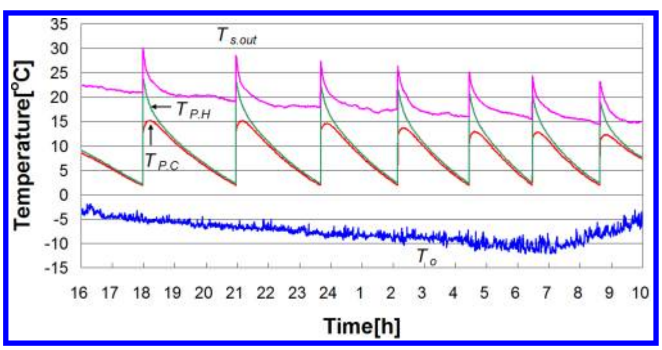
The exit temperature of storage tank, $T_{s,\mathrm{out}}$ started at 25°C and gradually dropped due to inflow of cold water and heat loss to the surroundings. Figure 9(b) shows ambient temperature drop to −10°C led to frequent activation of freeze prevention operation whose interval is about 2 h. Electric power consumption during 24 h was only 0.4 Wh and almost negligible compared to hot wire.

As previously mentioned, the automatic valve used in the experiment takes 30 s to be closed completely. During the closing, the pipe temperature rises near that of hot water in the storage tank. Therefore, the upper setting value is not significant unless a solenoid valve with rapid open and close is used. However, when cold climate with little sunlight sustains for a long time, the temperature of a storage tank significantly drops and water can continue to discharge if the temperature does not reach the upper setting value. So, it is appropriate to include a function to close the valve automatically when the water discharges for a certain time.

The results of hot wire tracing method are shown in Fig. 10, where Figs. 10(a) and 10(b) for separated and combined pipes, respectively. The pipes were set between 4°C and 11°C. Under −8°C ambient

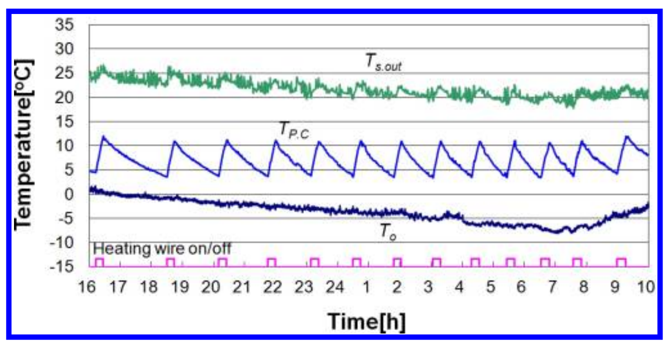


(a)

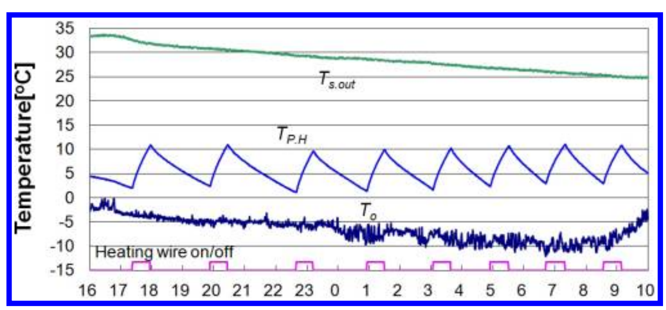


(b)

Fig. 9. Result graph of hot water tracing (a) 2010. 12.17–12.18 (b) 2010. 12.15–12.16.



(a)



(b)

Fig. 10. Result graph of heating wire tracing (a) separated pipes (2010. 2.15–2.16) (b) combined pipes (2011. 1.6–1.7).

temperature, the interval was 1 h and the number of hot wire operation was 13 times for 18 h with electric power consumption 1.2 kWh. Figure 10(b) shows combined pipes with one hot wire decreased the number of operation to eight times and electric power consumption to 1.1 kWh even in colder ambient temperature. The results are due to decreasing outer surface area of combined pipes like Fig. 2 compared to separated pipes. Hence, combined pipes in the hot wire tracing method saves initial construction cost by reducing hot wire length by half.

In combined pipes, one concern that arises is the fact that the temperature of the hot water will diminish as it passes through the hot pipe and transfers its heat to the cold pipe. However, such temperature drop is small since heat transferred time is short unless pipe length is exceptionally long, and thermal resistances between the two pipes prevent the heat transfer.

It is meaningful to compare energy usage between the existing hot wire tracing method and the newly proposed hot water tracing method. Under −10°C ambient temperature, hot water tracing method uses 0.4 Wh and hot wire tracing method uses 1.1 kWh. Additional advantage of hot water tracing method is semi permanent life expectancy other than very little electric power consumption.

The weakness has increased hot water discharge as ambient temperature drops as shown by Fig. 9. To deal with this problem, thicker insulator should be used. According to Fig. 7, increasing insulator thickness from 20 mm to 40 mm improves the duration by 1.5 times and decreases hot water discharge. There should be a further study on practical use of discharged hot water. Also, pump-circulation hot water tracing method without water discharge should be used in a climate with temperature less than −10°C.[5]

5. Conclusion

Combined piping hot water tracing method was newly proposed to solve burst by freeze problems in passive solar water heating system. Verification experiments conducted under cold climates for three years showed successful operations and appropriate heat exchange between heated hot water pipe to cold city water pipe.

The amount of hot water discharge depends on pipe length, diameter, insulator thickness and ambient temperature. Hot water of 0.27 L was discharged per 1 m of 15 A steel pipe in 25°C thermal storage tank. It is recommended to use 40 mm rather than 20 mm insulator to decrease hot water discharge. Also for no water discharge, it is desirable to use pump-circulation hot water tracing method in a colder region than −10°C.

Although combined piping is essential for hot water tracing method, it decreases electric power consumption and saves construction time and effort in the existing hot wire tracing method.

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