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Effective Use of Ground Source Heat Pump System in Traditional Japanese 'Kyo-machiya' Residences in Winter

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Abstract

Today, promoting the use of abundant renewable energy such as underground heat has become imperative. The preservation of the traditional wooden dwellings unique to Kyoto called Kyo-machiya has recently become a priority policy in Kyoto. However, owing to the poor airtightness and thermal insulation of Kyo-machiya, these dwellings require considerable energy to heat during winter. However, most Kyo-machiya are equipped with a well, and this study employs experiment and analysis to examine the practicablity of installing simple ground-sourced heat pump systems in the existing wells of Kyo-machiya. The efficient operation of the heat pump system is also investigated.

Keywords: ground source heat pump system; well water temperature; 'Kyo-machiya'; ground water flow

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1. Introduction

Owing to concerns for resource depletion and global warming, many countries worldwide have promoted the use of renewable energy [1]. Among these, underground heat is a consistently available energy source. In Japan, underground heat pump technology has begun to be utilized in large-scale office buildings, and further use is expected in the future [2]. However, several technical problems such as the high initial costs of equipment and

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installation that includes drilling costs, which are high in Japan, remain. In Japan, many traditional dwellings are designed to suit the local climate and lifestyle. Among these are the ‘Kyo-machiya’ unique to Kyoto, which are also an important cultural asset, the preservation of which has become a priority policy in Kyoto. However, room for improvement exists in traditional Kyo-machiya construction in terms of the indoor environment and heating costs. Kyo-machiya are designed to maintain occupant comfort in summer: however, comfort in winter is typically poor, and the dwellings consume considerable energy for heating. An interesting feature of Kyo-machiya is that most have a well. Therefore, if heat pump technology can be employed by utilizing the existing wells, the drilling costs can be reduced and a more comfortable indoor environment in winter with reduced energy consumption can be provided. Through experiment and analysis, this study aims to examine the practicability of employing an underground heat pump system and its optimization using a preexisting well of a Kyo-machiya.

Nomenclature		**Subscripts**	
c	specific heat [J/(kg K)]	b	antifreeze solution
ρ	density [kg/m^3]	s	ground soil
T	temperature [K]	w	well water
KS	heat transfer coefficient [W/K]	a	air
λ	thermal conductivity [W/(m K)]	e	evaporator
J	flow rate [kg/(m^2 s)]	r	refrigerant
V	unit volume [m^3]		

2. Heating experiment using a ground source heat pump system

2.1. Outline of the experiment

The experiment was performed in an existing Kyo-machiya constructed more than 150 years ago. In this typical dwelling, the outer and partition walls are made of soil without insulation. The structure is that of a rectangle extending from south to north that has many openings in the north and south facades, as shown in Fig. 1. (a). Contrary to typical residences, this dwelling has a well in the living space (LD) as shown in Figs. 1 (a) and (b). The well is approximately 80 cm in diameter and extends to a depth of approximately 9 m from the ground surface.

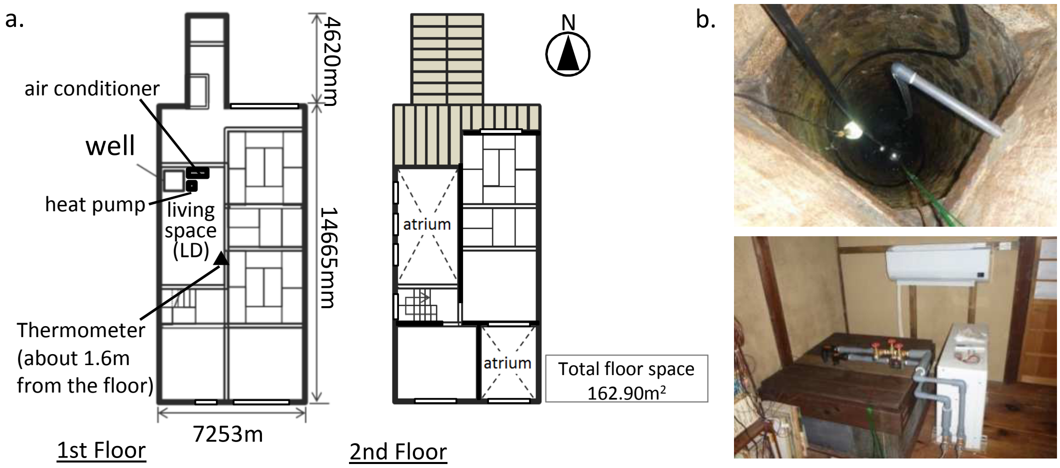

Fig. 1. Surveyed Kyo-machiya: (a) floor plan of the dwelling; (b) images of the well with the heat pump installed.

Prior to the experiment, only a kerosene fan heater had been used in the LD. A heat pump system was installed near the well in the dwelling in December 2013. In this system, a circulation pipe passes through the water in the well, and propylene glycol diluent antifreeze solution (circulating fluid for heat exchange between well and water and evaporator of heat pump) is circulated in the pipe. The heat extracted from the water is returned to the heat pump. During the experiment, the temperatures of air and water in the well and that of the LD were measured. The well water temperatures were measured at distances of 500 mm (lower region), 2500 mm (middle region), and 4500 mm (upper region) from the bottom of the well. The flow rate and temperatures of the antifreeze solution flowing out from the heat pump into the well, the temperature of the antifreeze solution returning from the well to the heat pump were measured.

2.2. Experimental results

Figure 2 (a) shows the temperatures of the well and LD before and after the installation of the heat pump. Once the heating by the heat pump began, the average living room temperature rose by approximately 4.0 °C. The well water temperature, which had remained nearly constant at 18.0 °C decreased after heat pump operation. When the heat pump was operated for 12 − 15 hours a day at a room of about 18 °C − 20 °C for two weeks, the well water temperature was reduced by approximately 13 °C. Because the temperature of the lower region of the well was lower than that of the upper region, heat exchange appears to have possibly occurred in mainly the lower region. As the operational period of the heat pump was reduced, the well water temperature rose relatively quickly. Therefore, ground water appears to flow in this area.

Using the measured temperatures and the flow rate of the antifreeze solution, the heat gain from the well Q [W] is calculated by the equation as follows.

$$Q = c_b \rho_b J_b \left(T_{in} - T_{out}\right) \tag{1}$$

where T_{in} and T_{out} are the temperatures [K] of the antifreeze solution at the heat pump inlet and outlet, respectively. Although the density of propylene glycol varies with temperature and its specific heat varies with both temperature and density, they are both assumed constant, where $c_b = 4.1 \times 10^3$ [J/(kg·K)] and $\rho_b = 1.02 \times 10^3$ [kg/m^3]. The heat gain was calculated according to the flow rate shown in Fig. 2(b). Although the flow rate was reduced by approximately 35 % after 12 February, the heat gain decreased only by 18 % because the temperature difference of the antifreeze solution at the inlet and outlet of the heat pump increased.

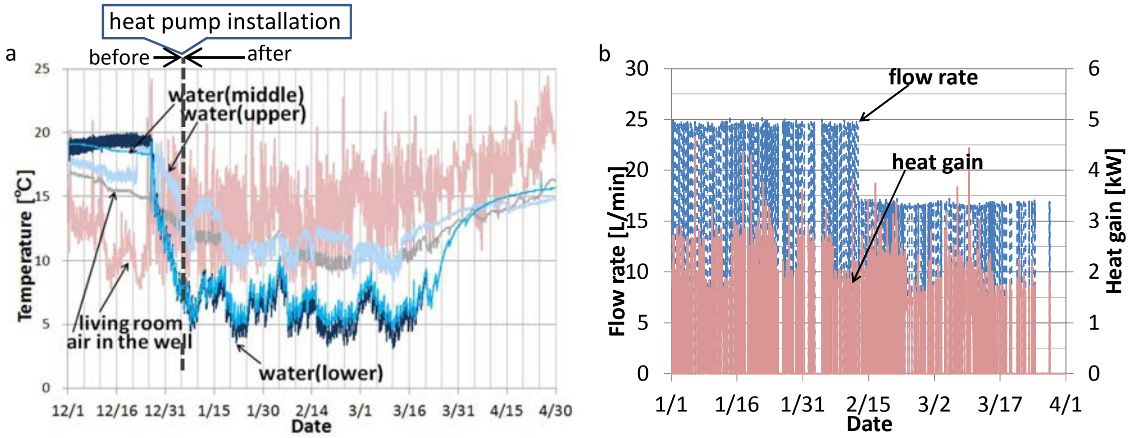

Fig. 2. Experimental results: (a) temperature changes; (b) heat gain and flow rate of the antifreeze solution.

3. Numerical analysis of the temperature of well water and heat gain of heat pump

3.1. Outline of the analysis

An analytical model corresponding to the experimental conditions is proposed. The simplified two-dimensional model shown in Figure 3 with the described boundary conditions comprises soil, air and water. The evaporation temperature of the heat pump refrigerant is assumed as −15 °C. Climatic data for Kyoto obtained from the Japan Meteorological Agency [3] is used to establish the outside air temperature. The measured air temperature of the well, indoor temperature and flow rate of the antifreeze solution are used as inputs. The calculation period is 151days from 1 January to 31 May 2014, and the operational period of the heat pump is set from 1 January to 31 March 2014.

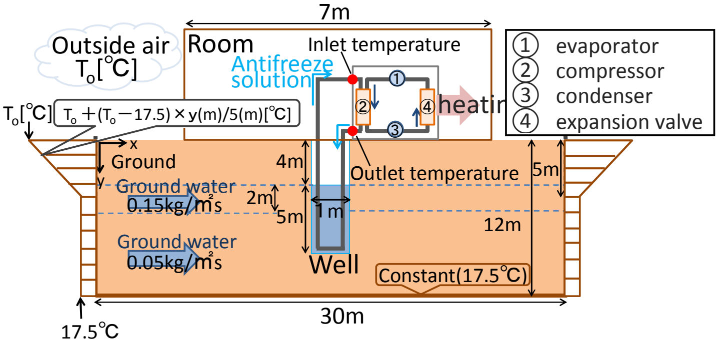

Fig. 3. Schematic of the simplified two-dimensional analytical model including boundary conditions.

Heat balance equations for ground soil, well water, and antifreeze solution are given by Eqs. (2), (3) and (4) [4]. Judging from the measurement results described above, heat transfer due to groundwater flow can not be neglected. Therefore, both thermal conduction in the ground and heat transfer with ground water flow were considered. Groundwater flow is assumed to occur only in the horizontal direction. Convective heat transfer due to buoyancy was also considered in the well water. Table 1 lists the material properties of the soil and water. Table 2 lists the heat conductance values between the antifreeze solution and both the well water and the refrigerant in the evaporator. These values were determined to ensure agreement between the calculated and measured results. The heat conductance between the antifreeze solution and well water was assumed to depend on the depth of the well. Using these equations and conditions, the temperatures of the antifreeze solution and well water were calculated.

$$c_s\rho_s\frac{\partial T_s}{\partial t}=\frac{\partial}{\partial x}\left(\lambda_s\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_s\frac{\partial T}{\partial y}\right)-c_wJ_g\frac{\partial T}{\partial y} \tag{2}$$

$$c_w\rho_wV_w\frac{\partial T_w}{\partial t}=V_w\frac{\partial}{\partial x}\left(\lambda_w\frac{\partial T_w}{\partial x}\right)+V_w\frac{\partial}{\partial y}\left(\lambda_w\frac{\partial T_w}{\partial y}\right)-c_wJ_gV_w\frac{\partial T}{\partial y}-c_wJ_bV_w\frac{\partial T}{\partial x}-K_wS_w(T_w-T_b)\delta(x-x_0)\delta(y-y_0) \tag{3}$$

$$c_b\rho_bV_b\frac{\partial T_b}{\partial t}=K_iS_i(T_i-T_b)-c_b\rho_bV_b\left(\frac{\partial T_b}{\partial x}\right) \tag{4}$$

where (x_0, y_0) is a point in the well water without through the pipe, and J_b is the flow rate of the convection by buoyancy.

Table 1. Material properties used in the calculation.

	c (J/kgK)	ρ (kg/m^3)	λ (W/mK)
Soil	1100	1622	1.0
Water	4200	998	0.6

Table 2. Heat conductance value between the antifreeze solution and each substance

	KS (W/K)
Water (0-2m from the water surface)	1.413
Water (2-5m from the water surface)	4.239
Refrigerant	1012.65

3.2. Comparison of the calculated and measured results

Figure 4 (a) shows a comparison between the measured and calculated results for the water temperatures at the upper, middle and lower regions of the well. The calculated water temperature at each depth agrees well with the measured result. Figure 4 (b) shows the moving average of the calculated and measured heat gains at 15 minutes interval. The antifreeze solution flow rate decreased from about 25.0 L/min to about 16.5 L/min after 12 February. Although the calculated heat gain decreased immediately after the flow rate has decreased, the measured result increased first and then decreased. This is because the measured temperature difference between the heat pump inlet and outlet became larger. Although the proposed analytical model should be improved, the calculated results agree reasonably well with the measured results. Therefore, we employ this model to investigate more efficient heat pump system operation design in the next section.

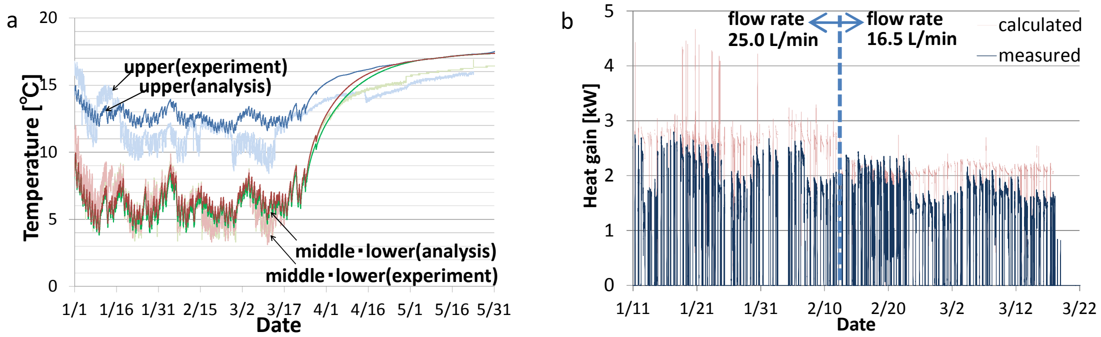

Fig. 4. Comparison of calculated and measured results: (a) well water temperatures; (b) heat gain.

3.3. Influence of the heat pump operation on well temperature and heat gain

The three cases based solely on different heat pump system operating times and antifreeze flow rates, as listed in Table 3, were calculated by the proposed analytical model. Case 1 is a reference case. In Case 2, the daily heat pump operating time is increased by 6 hours, and in Case 3, the antifreeze solution flow rate is reduced by half. The calculated results of the three cases are compared to develop a more efficient use of the heat pump system.

Table 3. Heat pump system operating times and antifreeze solution flow rates.

	Case1 (Reference)	Case2	Case3
Operating time	8:00 - 20:00 (12h/day)	6:00 – 24:00 (18h/day)	8:00 – 20:00 (12h/day)
Flow rate [L/min]	25.0	25.0	12.5

Figures 5 (a) and (b) show the calculated temperatures of the well water at the upper and lower regions, respectively, for the three cases. The temperature of the well water near the middle region was nearly uniform for all cases. Figure 5 (c) shows the daily average of the calculated heat gain from the well in each case.

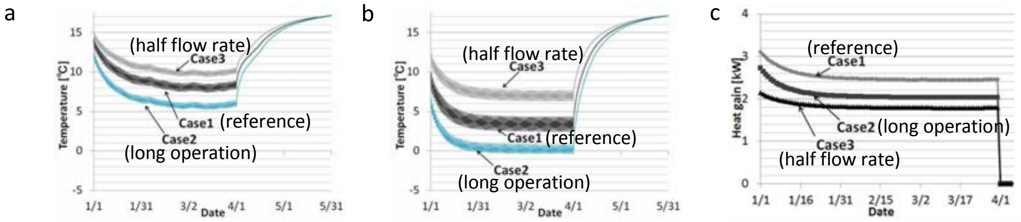

Fig. 5. Analytical results of the three cases:
(a) well water temperature at the upper region; (b) well water temperature at the lower region; (c) daily average heat gain.

As shown in Figs. 5(a) and (b), when the daily operating time is increased by 6 h (Case 2) relative to that of the reference case (Case 1), the well water temperature at the upper region is approximately 2.5 °C lower and at the lower region is reduced by approximately 3.0 °C after 3 months, relative to those of the reference case. When the antifreeze solution flow rate is halved (Case 3), the well water temperature at the top region increases by approximately 2 °C and the bottom region increases by approximately 3.5 °C, relative to those of the reference case over the same period. The water temperature difference between the top and bottom regions of the well is increased in Case 2 and reduced in Case 3. As shown in Fig. 5(c), relative to Case 1, an increase in the daily operating time by 6 h (Case 2) results in a reduced daily average heat gain by approximately 0.5 kW. Relative to Case 1, when the antifreeze solution flow rate is halved (Case 3), the average daily heat gain is approximately 0.8 kW less.

3.4. Discussion

When the flow rate of the antifreeze solution is reduced, the calculated temperature difference of the solution between the heat pump inlet and outlet is also reduced, resulting in a lower calculated heat gain. An increased daily heat pump operating time results in a reduced well water temperature owing to a reduced period for temperature restoration. Moreover, the two dimensional model provides a groundwater flow rate larger than the measured flow rate. A three dimensional model is expected to obtain an improved antifreeze solution flow rate and heat gain.

4. Conclusion

Through experiment and analysis, this study examines the practicability of a simple ground-sourced heat pump system in the existing wells of Kyo-machiya. The measured results verified that the existing well has sufficient heating capacity for a heat pump system. The temperature of the well water, which was reduced by heat pump operation, was rapidly restored when heating was stopped, probably owing to groundwater flow at the experimental site. The analysis revealed that the daily heat pump operating time and antifreeze solution flow rate affect the efficiency of the heat pump system.

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