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Effective use of a ground-source heat-pump system in traditional Japanese "Kyo-machiya" residences during winter

Kana Hagihara, Chiemi Iba*, Shuichi Hokoi

Kyoto University, Graduate School of Engineering, Kyoto daigaku-katsura, Nishikyo-ku, Kyoto 615-8540, Japan

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ABSTRACT

Today, promoting abundant renewable energy use, such as heating system using ground-source heat, has become imperative. The preservation of traditional wooden dwellings unique to Kyoto called Kyo-machiya has recently become a priority policy in Kyoto, Japan. However, due to their poor airtightness and thermal insulation, Kyo-machiya dwellings require considerable energy to heat during winter. Most Kyo-machiya dwellings have a well from which residents are supplied source water for drinking, washing and other purposes. Well water can potentially be harvested as a heat source, providing a comfortable, low-consumption indoor environment during winter months. In this study, an experiment was conducted to examine the practicability of installing simple ground-sourced heat-pump systems in the existing wells of Kyo-machiya dwellings. A heat pump system comprising an indoor unit and outdoor unit was installed near a well in a Kyo-machiya dwelling. Antifreeze solution was circulated in a pipe that passed through the well water. The heat captured from the water was returned to the heat pump. Heat gain from the well water was calculated from the measured temperature and the flow rate of the circulating antifreeze solution. Furthermore, an analysis model reproducing the experiment is suggested to examine the efficient operation of the heat-pump system.

1. Introduction

Concerns about resource depletion and global warming have prompted many countries worldwide to promote the use of renewable energy. One form of renewable energy, underground heat, is a consistently available energy source that has been mainly utilized with a heat-pump system [1–3]. As the heat gain during heating season (or exhaust heat in cooling season) depends on the local conditions such as climate, ground properties, groundwater flow, and requirements of residents, several studies focusing on a particular region have been conducted [4–7]. Many researchers have indicated that the groundwater flow greatly effects thermal dispersion in the ground [8–11]. Many previous studies targeted the borehole heat exchanger system and examined energy efficiency or geothermal productivity and sustainability using in situ measurements and calculations with various numerical models [12–14]. Some studies investigated the geothermal heat-pump system from the economic viewpoint [15,16].

In Japan, underground heat-pump technology has begun to be utilized in large-scale office buildings, and further use is expected in the future [17]. However, several economic problems still exist, such as high initial costs of equipment and installation including drilling costs, which are high in Japan. Matsumoto et al. examined the thermal storage characteristics of soil using experiments and numerical analysis to prove that it is an effective heat source for the heat pump [18]. Ito et al. proposed a design method for a heat-pump system to optimize thermal efficiency while considering other design objectives such as saving energy and minimizing equipment costs [19].

In addition to considering the climate and ground properties of a region, we had to consider the various types of traditional dwellings designed to suit the local climate and lifestyle [20,21]. Among these is the 'Kyo-machiya', which is unique to Kyoto, Japan, and is also an important cultural asset. Today, approximately 47,000 Kyo-machiya dwellings exist in Kyoto city [22], and their preservation has become a priority policy in Kyoto city. However, traditional Kyo-machiya construction can be improved further in terms of the indoor environment and heating costs. Kyo-machiya dwellings are designed to maintain occupant comfort in summer: however, these dwellings can become uncomfortable in winter, and they consume considerable energy for heating because of the poor insulation and lack of airtightness. Traditional Kyo-machiya dwellings have an outer wall made of soil without insulation, and usually, they have wooden window frames with paper screens called *Shoji*. In partic-

* Corresponding author.
E-mail address: iba@archi.kyoto-u.ac.jp (C. Iba).

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Nomenclature

c	Specific heat [J/(kg K)]
J	Flow rate [kg/(m^2 s)]
K	Heat transmission coefficient [W/(m^2 K)]
S	Area [m^2]
T	Temperature [K]
V	Volume [m^3]
x,y,z	Axis of coodinates
α	Heat transfer coefficient [W/(m^2 K)]
λ	Thermal conductivity [W/(m K)]
ρ	Density [kg/m^3]
$\partial/\partial n$	Normal direction differential on boundary between well water and refrigerant

Subscripts

a	Air
b	Antifreeze solution
buo	Buoyancy
e	Evaporator
g	Groundwater
in	Inlet of heat pump
out	Outlet of heat pump
r	Refrigerant
s	Ground soil
w	Well water

ular, the appearance of the traditional façade (as seen in Fig. 1) is quite important to the residents; therefore, many residents resist plans to enclose Kyo-machiya dwellings with external insulation.

An interesting feature of Kyo-machiya dwellings is that most of them have a well. Previously, the well water was used for drinking, washing and other daily use; however, recently it is mainly used only for water-sprinkling and fire-fighting purposes. This well water can be utilized as a heat source for heating these dwellings during winter months. If heat-pump technology uses the existing wells, the drilling costs can be reduced and a more comfortable indoor environment can be provided in winter with reduced energy consumption.

Through experimentation and analysis, this study aims to examine the practicality of an underground heat-pump system employed in the preexisting well of a Kyo-machiya dwelling.

2. Heating experiment using a ground-source heat-pump system

2.1. Surveyed dwelling

The experiment was performed in an existing Kyo-machiya dwelling constructed more than 150 years ago. In this typical dwelling, the outer and partition walls are made of soil without insulation. The thermal resistance of the soil wall is approximately 0.1–0.12 m^{2}K/W (thermal conductivity is assumed as approximately 0.5 W/mK, and the thickness is generally 50 mm and partially 60 mm). Although it has low thermal insulation performance, the heat capacity of the wall is fairly large (approximately 1150 kJ/m^{3}K).

The airtightness is extremely poor. The structure is rectangular extending from south to north and having many openings in the north and south facades, as shown in Fig. 2. Contrary to typical modern residences, this dwelling has a well in the living space (a combined living and dining room), as shown in Figs. 2 (a) and 4 .

The schematic cross-section of the well is shown in Fig. 3(a). The well is approximately 80 cm in diameter and reaches a depth of approximately 9 m below the ground surface. The side wall of the well is made up of stones, with the gaps between the stones filled with mortar. In most cases, well water springs up from the bottom of the well; however, in some cases, it infiltrates the well through the side wall. Fig. 3(b) shows the time profile of the well-water depth and precipitation. The well-water depth seems to be strongly affected by the amount of precipitation.

2.2. Heat pump system installation

Prior to the experiment, only a kerosene fan heater was used in the living/dining room (LD). A heat-pump system was installed near the well in the dwelling in December 2013 (Fig. 4). Table 1 shows the global performance of heat pump system. The Rated heating capacity was 5.0 kW, suitable for the room in a wooden house area of 18–23 m^2. Although the LD area of this house was approximately 20 m^2, heating capacity was expected to be possibly insufficient because this dwelling has poor thermal performance. In this system, a circulation pipe passes through the water in the well, and an antifreeze (propylene glycol diluent) solution is circulated in the pipe, because the evaporator temperature could become below 0 °C. The heat extracted from the water is returned to the heat pump and used as a heat source. The specifications of the pipe and antifreeze solution are shown in Table 2.

In this system, the amount of blowout from the indoor unit is determined according to both the difference between the set

Fig. 1. Images of the traditional façade of Kyo-machiya dwellings.