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Research paper

Potential for using water reservoirs as heat sources in heat pump systems

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HIGHLIGHTS

- Potential for using reservoirs as a heat source for heat pumps was discussed.
- Thermal stratification was observed in summer by a measurement in Hiroshima.
- Measured temperatures were reproduced by computer simulation.
- Indices to evaluate heat source potentials were proposed.
- Winter weather conditions influence on both the summer and winter indices.

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ABSTRACT

There are many water reservoirs intended for agricultural applications or flood control in western Japan. These reservoirs may offer energy savings because their water is usually at a higher temperature in winter and lower temperature in summer than that of ambient air. The present work assesses whether thermal energy stored in these reservoirs can be used as heat sources for heat pump systems. Water temperatures were measured over 1 year at six different reservoir depths. During summer there was thermal stratification, in which water temperatures were widely distributed between 10 °C and 30 °C. During winter, active natural convection provided a stable vertical temperature distribution. A one-dimensional fluid dynamics model enabled reproduction of the measured water temperatures. Then, based on an index for cooling in summer (P_c) and another for heating in winter (P_h), the potential of using 16 reservoirs as heat sources was evaluated. These indices are related to differences between ambient air temperatures and water temperatures calculated near reservoir bottoms. Winter weather conditions were found to statistically affect both P_c and P_h. Weather conditions have little influence on water temperatures near reservoir bottoms in summer. Cold winters produce large values of P_c.

1. Introduction

The use of unutilized energy in heat pump systems has possibilities for saving energy in cooling and heating applications. Such energy usually resides in bodies of water or in ground deposits of gravel, sand, and rock filled with air and water. These sources maintain relatively constant temperatures because their heat capacities are large compared with that of air. A GSHP system is a common one that uses ground, groundwater, or surface water such as in lakes, reservoirs, rivers or sea as a heat source and/or heat sink for heat pumps [1,2]. In general, GSHP systems have higher annual efficiencies than conventional air source systems, primarily because of the heat source temperature [3].

Although use of the ground directly or indirectly through heat exchangers is well known and has spread to many countries, surface water is also a potential heat source, provided that an appropriate body of water is near the heat demand, such as residential housing, office buildings, or other commercial structures. Direct use of heat sources without heat pumps generally leads to higher efficiencies [4]. Cornell University operates a cooling system in which cold lake water around 5 °C is pumped from a depth of 76 m and used directly for cooling campus buildings [5]. SWHPs are also effective for use with relatively shallow ponds. Kavanaugh monitored heat source temperatures [6] and actual COPs [7] in several

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Abbreviations: GSHP, ground source heat pump; SWHP, surface water heat pump; COP, coefficient of performance; DYRESM, dynamic reservoir simulation model.

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Nomenclature

c	cloud cover ratio [−]
d	rainfall [mm]
P	heat source potential of reservoirs [K h]
Q	integral of global solar radiation [MJ/m^2]
RH	relative humidity [%]
Ta	ambient air temperature [°C]
Tw	water temperature [°C]
t	time [h]
v	wind velocity [m/s]
Greek symbols	
ε	relative error [−]
η	attenuation coefficient for shortwave radiation [1/m]
Subscripts	
c	cooling period
cal	result from calculation
g	heat gain period
h	heating period
mea	result from measurement
r	heat release period
y	year

residential houses in the southern United States. Practical examples are also found in Norway, Sweden, Japan, and China [4,8]. An experimental study was conducted by Büyükalanca et al. [9] based on the use of river water.

Several design tools such as EED [10], GchpCalc [11] and Groundclub [12–15] have already been developed for GSHP systems, in which the theory of heat conduction is applied to the use of ground sources. However, only a few studies have addressed procedures for designing SWHP systems. Kavanaugh illustrated design conditions such as capacities of heat pumps and required coil lengths in the southern United States [6,7]. Cantrell and Wepfer calculated water temperatures including influences of heat release from condensers based on energy balance equations for shallow ponds, assuming a lumped parameter system [16]. Pezent and Kavanaugh proposed a lake model in which energy balances in vertically three zones were solved [17]. Wang et al. developed numerical models to predict water intake temperatures for open-loop SWHP systems [18].

For appropriately evaluating system performance and establishing the design procedure, discerning natural behavior of the heat source is important as a first step. Thermal stratification is a characteristic of lakes and reservoirs with low flow rates and exchange rates compared with rivers or sea typically with high flow rates. Thermal stratification occurs from spring to summer, when large increases of solar heat on the surface produce vertical density differences. Furthermore, the presence of a thermocline has been reported to be correlated with daily weather changes [19]. Hattermer and Kavanaugh [20] collected temperature data for various types of lakes in the United States and described thermocline differences.

The purpose of the present study was to clarify the natural behavior of reservoirs intended for agricultural applications or flood control in western Japan and to quantify the potential as heat sources in SWHP systems. Water temperature profiles in a reservoir at 5-m depth were measured and compared with values from computer simulations using the one-dimensional hydrodynamic model DYRESM [21,22]. A basic reservoir model was constructed by parametric analyses to diminish error between calculations and measurements. This model was then used to compute various temperature profiles under different boundary conditions, such as solar radiation, air temperature, and wind velocity. The potential of each reservoir was evaluated using an index obtained by integrating differences of air and water temperatures near reservoir bottoms. Finally, weather conditions leading to high potentials for the use of SWHP systems in western Japan were identified.

2. Measurement of water temperatures

2.1. Description of measurements

Vertical distributions of water temperature were continuously measured near the center of a reservoir in Hiroshima Prefecture of southwest Japan (Table 1). The reservoir has surface area ~25,000 m^2 and depth 5.5 m at the sampling point. Because the reservoir provides flood control and water storage, the water level is kept relatively constant throughout the year.

2.2. Seasonal variations

Fig. 1 compares measured water temperatures (Tw_{mea}) at depths 1 and 5 m on the basis of variations of air temperature (Ta) and rainfall amounts during one year, beginning November 2012. Ta and rainfall were taken from hourly weather data of the Automated Meteorological Data Acquisition System (AMeDAS) [23]. Both Tw_{mea} values decreased uniformly from the end of October and reached a minimum 4.5 °C at the end of January. The vertical difference increased beginning in February, to a maximum 17.7 °C in mid August. At certain times in summer, vertical temperature differences disappeared or decreased rapidly, e.g., on 20 June, 24 August, and 4 September. These dates had heavy rains, so the declines of vertical temperature difference may have been attributable to accelerated inner mixing caused by intense rainstorms.

Differences between Tw_{mea} and Ta indicate the effectiveness of using reservoirs as heat sources for heat pumps. At depth 5 m, Tw_{mea} remained higher than Ta over many hours each day in winter, and it was comparable to the daily maximum Ta. Larger differences in summer are attributed to stable variations of Tw_{mea} at 5-m depth.

2.3. Vertical variations

In summer, thermal stratification ideally separates into three zones [1]. Large heat gains generate higher and uniform temperatures in an upper zone, called the epilimnion, whereas relatively low temperatures persist in a bottom zone, called the hypolimnion. Between these two is the intermediate zone, the metalimnion, which has large density differences and contains the thermocline.

Table 1
Description of Kadowaki Reservoir and its measured temperatures.

Reservoir	Name	Kadowaki reservoir
	Location	Hiroshima Prefecture, Japan Latitude 34°25′N, Longitude 132°E.
	Size	25,000 m^2
	Depth	Approximately 7.0 m at deepest point Approximately 5.5 m at measurement point
Measurements	Start date	21 September 2012
	Measured depths	0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 m from water surface
	Sensors	Thermistor thermometers with USB data loggers Range: −35 to +80 °C Accuracy: ±2 °C
	Interval	1 h