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Analysis of ground source heat pumps with horizontal ground heat exchangers for northern Japan

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ABSTRACT

Computer simulation and analysis of a ground source heat pump system with horizontal ground heat exchangers operating in heating (max 5.5 kW) and cooling (max 3.3 kW) mode was carried out for a typical residential house, with 200 m^2 of living space, located in Sapporo (Japan). In spite of high electricity rate, the ground source heat pump system is more beneficial alternative for space heating than an oil furnace and an electric resistance system. Besides, the heat pump technology offers relatively low thermal degradation of the ground environment, lower cost of heating and cooling, higher operating efficiency than electric resistance heating or air-source heat pump and is environmentally clean, i.e. without greenhouse gas emission, if the electricity is generated from renewable energy resources, such as wind and solar. The use of the cooling mode can provide further benefits like a shorter investment payback and human thermal comfort in summer. As a result, application of horizontal loops for new and retrofit residential and commercial use in northern Japan is feasible particularly in farmland areas.

1. Introduction

Energy resources of Japan are very limited and for that reason about 97% of oil and natural gas has to be imported; about half of these primary energy sources is converted to the electric power; the commercial and residential sector accounts for about 27% of the total energy consumption; of this, space heating and air conditioning account for 24.5% of the total household electricity consumption [1]. In rural areas of northern Japan, continuous heating (oil-fuelled furnaces) is needed in winter period for numerous greenhouses packed with a large variety of vegetables, while in the mainland Japan huge energy demand for air conditioning arises in summer time. Due to these reasons Japan may face in the near future serious uncertainty regarding the economic growth, keeping up a high living standard, and maintaining international competitiveness. These concerns have stimulated an interest in ground source heat pumps (GSHP) as this technology offers considerable savings of the primary non-renewable energy resources while keeping the surrounding environment nearly intact. Besides, it also offers lower cost of heating/cooling and higher operating efficiency (COP > 3) than electric resistance heating or air-source heat pumps. Potential applications of this technology are in heating/cooling buildings, growing vegetation in greenhouses, drying crops, heating water at fish farms, pasteurizing milk, etc. Moreover, the farming sector offers lesser restriction on the ground availability which is beneficial to the use of horizontal GHE; this in turn could reduce problems related to unstable geology and high installation costs of vertical GHE. The impacts of low thermal conductivity (λ) of volcanic soils on the length of the GHE and long term use of combined heating and cooling operation on the ground environment (degradation of ground thermal and moisture storage capacity) remain however unknown. Therefore, elucidation of these issues is the principal objective of this paper. In addition, this paper intends to examine the potential use of GSHP with a horizontal GHE for residential space heating and cooling in northern Japan.

2. Ground source heat pump basics

A GSHP unit is an assembly of an electrically driven compressor, two heat exchangers (refrigerant-air and refrigerant-water), and an expansion valve (throttle). Its primary aim is utilization of the ground as a heat source in winter and as a heat sink in a summer period. In winter/summer, natural heat of the ground is absorbed/rejected by an antifreeze solution flowing in the GHE, which can be a series of plastic pipes installed below the ground surface (Fig. 1) or submersed in a water reservoir (lake, river, sea, ocean, etc.). Majority of GSHP systems use closed-loop GHEs installed

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Nomenclature

COP	coefficient of performance (–)
$\mathrm{COP_C}$	seasonal cooling coefficient of performance (–)
$\mathrm{COP_H}$	seasonal heating coefficient of performance (–)
$\mathrm{COP_O}$	annual overall coefficient of performance (–)
GSHP	ground source heat pump (–)
GHE	ground heat exchanger (–)
HE	heat exchanger (–)
Ke	Kersten's number (–)
Q_C	cooling demand provided by the GSHP (kW)
Q_H	heating demand provided by the GSHP (kW)
$Q_{\text{cooling-load}}$	cooling load (MJ/month)
$Q_{\text{heating-load}}$	heating load (MJ/month)
S_r	degree of soil saturation (–)
T	temperature (°C)
W_o	total energy consumption (kJ)
$W_{\text{o-H}}$	total energy consumption in heating season (kJ)
$W_{\text{o-C}}$	total energy consumption in cooling season (kJ)
$W_{\text{o-O}}$	annual energy consumption (kJ)
W_{co}	electrical energy supplied to a heat pump compressor (kJ)
W_{fan}	electrical energy supplied to a heat pump circulation fan (kJ)
W_{sup}	electrical energy required for supplementary heating (kJ)
W_{pump}	electrical energy supplied to a circulation antifreeze-solution pump (kJ)

Greek symbols

λ	soil thermal conductivity (W/mK)
λ_{dry}	thermal conductivity of dry soil (W/mK)
λ_{sat}	thermal conductivity of saturated soil (W/mK)
θ_w	volumetric soil water content (–)

horizontally or vertically. The GSHP with a closed-loop GHE offers a coefficient of performance (COP) between 3 and 5. In the lower COP range, single-speed rotary or reciprocating compressors are used, while scroll compressors are common in mid-range units. The high COP units use two-speed compressors and/or variable-speed indoor fan motors. For maximum cost-effectiveness, the GSHP is usually sized to meet 60–70% of the total maximum load demand (space heating and domestic hot water). Occasional peak heating demand during severe weather conditions can be met by using a supplementary heating system (wood stoves, electric resistance heaters, etc.).

3. Energy analysis of ground source heat pumps

Evaluation of the GSHP thermodynamic performance is based on the following energy related characteristics. The total energy consumption (W_o) of the GSHP system includes all system components:

$$W_o = W_{co} + W_{fan} + W_{sup} + W_{pump}, \tag{1}$$

The seasonal heating COP:

$$\mathrm{COP_H} = \frac{Q_H}{W_{\text{o-H}}}, \tag{2}$$

The seasonal cooling COP:

$$\mathrm{COP_C} = \frac{Q_C}{W_{\text{o-C}}}, \tag{3}$$

Finally, the annual overall COP is defined as follows.

$$\mathrm{COP_o} = \frac{Q_H + Q_C}{W_{\text{o-H}} + W_{\text{o-C}}}, \tag{4}$$

where W_{co} is electrical energy supplied to a compressor; W_{fan} is electrical energy supplied to an indoor circulation fan; W_{pump} is electrical energy supplied to a circulation pump of antifreeze solution; W_{sup} is electric energy required for supplementary heating, $(W_{sup})_{heating} = Q_{\text{heating-load}} - Q_H$, or cooling, $(W_{sup})_{cooling} = Q_{\text{cooling-load}} - Q_C$; Q_H and Q_C are the heating and cooling demand provided by the GSHP system, respectively. It is assumed that the efficiencies of the circulation pump and its electric motor are 70% and 90%, respectively.

4. Methodology of computer simulation

4.1. Meteorological and geological considerations

Computer simulation of a GSHP system is based on comprehensive daily average meteorological data input (e.g. ambient temperature, solar radiation, wind speed, precipitation, cloudiness, etc.). The data used was obtained from National Agricultural Research Center for Hokkaido Region (NARC) in Hitsujigaoka, Sapporo, covering a one-year period from September 1998 to August 1999. The ground geological information (Table 1) was also provided by the NARC from one of its experimental site in Sapporo. It was assumed that the ground domain was made of two soil layers, namely: Kuroboku soil (0–0.20 m); Hokudai soil (0.20–6.0 m). Soil thermal conductivity (λ) for frozen and unfrozen soils follows the experimental data by Suzuki et al. [2], fitted to Johansen model [3]:

$$\lambda = \lambda_{dry} + Ke\left(\lambda_{sat} - \lambda_{dry}\right), \tag{5}$$

where

$$Ke = a + b\left[\frac{S_r - c}{d}\right]\left[\frac{|S_r - c|}{d}\right]^{-e}. \tag{6}$$

The values of fitting coefficients for Eq. (6) are given in Table 2. The degree of saturation (S_r) is defined as the ratio of volumetric water content (θ_w) to soil porosity. The λ_{dry} and λ_{sat} for Eq. (5), as given in Table 3, were obtained by extending the trend of experimental data to dryness ($S_r = 0$) and saturation ($S_r = 1$), respectively. The S_r in the cases of frozen soils relates to the initial water content before freezing.

4.2. Housing considerations

Seasonal heating and cooling loads (September 1998–August 1999) were estimated for a typical house (200 m^2 of living space) in Sapporo requiring about 59.6, 3.80 and 20.0 GJ/year for heating, cooling and domestic hot water, respectively. The heating operation was applied from October 1998 to June 1999 with a peak heating load of 5.5 kW. Fig. 2 displays monthly variation of the heating load. The cooling operation was assumed from 15th of June to 15th of September 1999 with a peak cooling load of 3.3 kW. For a given peak heating load of 5.5 kW, two heat pump units were chosen from *WaterFurnace Premier* series models [4] with nominal heating