Energy and Buildings 49 (2012) 294–299

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Groundwater heat pump selection for high temperature heating retrofit

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ARTICLE INFO

Article history:
Received 21 January 2012
Accepted 17 February 2012

Keywords:
High temperature radiator heating
Heat pump
Low temperature groundwater
Seasonal COP
Exergy

ABSTRACT

Retrofitting of fossil fuel powered hot water radiator heating systems of the existing buildings by groundwater heat pumps can provide significant energy savings followed by economic and environmental benefits. The paper describes the procedure for selection of optimal low-temperature groundwater heat pump vapor compression cycle based on thermodynamic analysis of applied high temperature heat pump heating system. In comparative energy and exergy analysis observed are six different heating cycles, five of which utilize two-stage refrigerant compression, and one operate as basic one-stage heat pump system with an auxiliary heater. The systems validation is performed accounting strongly for the boundary conditions of the selected location.

1. Introduction

A significant part of total energy consumption in most Southeast European countries is used for residential and office buildings heating. The heating system predominantly utilized in urban settlements is high temperature water heating, either as connected to district heating network or, frequently, with local fossil fuel powered boilers as a heat source. In the second case the environmental impact of pollutants emissions in densely populated urban areas is especially harmful and therefore the existing buildings with hot water central heating systems should be considered the main target of energy efficiency measures.

Utilization of ground source heat pump heating systems, is gaining in importance globally. Heat pump heating systems that use groundwater as heat source (*open loop systems*) have many advantages over *closed loop systems* that extract heat from surrounding soil. In an open loop systems a risk of direct environmental pollution is insignificant since the possible refrigerant leakages are restricted to the heating substation or engine room of the facility, and the heat source temperature deterioration, common by closed loop systems, can be successfully avoided by appropriate water discharge technique [1,2], enabling a long term sustainable exploitation of groundwater resource. Furthermore, the heat extraction in an open loop system is more intense, which contributes to the overall heat pump system efficiency.

In newly built residential and office buildings, one stage ground source heat pump systems have been successfully used in various low temperature heating applications. In case of retrofitting of high temperature heating systems in existing buildings one stage systems are generally considered inefficient due to the temperature requirements, and the more complex layouts of vapor compression heat pumps need to be assessed. Nevertheless, for efficient operation and acquiring the maximal energy and cost savings effects of heat pump heating system with ground water as the heat source, a selection of location optimized vapor compression cycle is of primary importance.

Shallow groundwater is frequently found and various authors have addressed possibilities of its utilization in heating applications. Milenic et al. [3] suggested the criteria for use of groundwater in systems of geothermal heat pumps. Kara and Yuksel [4] evaluated use of low temperature geothermal energy by means of water to water heat pump. Wang et al. [5] developed and experimentally validated high temperature heat pump using geothermal water for heat recovery and building heating. Hepbasli and Akdemir [6] conducted energy and exergy analysis of ground source heat pump system, and Kodal et al. [7] a performance analysis of a two-stage heat pump. Concerning the comparison of vapor compression cycles used in heat pump heating applications, Bertsch and Groll [8] theoretically and experimentally analyzed three different types of two-stage air source heat pumps in order to find solution for system performance drop caused by large differences between heat source and heat sink temperatures. Recently, authors have focused on evaluation of the effectiveness of ground source heat pumps for heating and cooling applications in buildings. For example, Hepbasli and Balta [9] have modeled and evaluated performance of a heat pump system utilizing a low temperature geothermal resource, and energy and exergy analysis methods were used to assess the system performance based on the experimental data. Importance of exergy analysis of vapor compression heat pump systems has been stressed by Jan [10] and Akpinar and Hepbasli

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0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2012.02.028

Nomenclature

COP	coefficient of performance
$\dot{E}x$	exergy (kW)
h	duration of a typical heating season (h)
P	heat pump power consumption (kW)
$\dot{Q}_h$	heating load (kW)
$\dot{Q}_{h,n}$	design heating load
$\dot{Q}_{gw}$	heat transfer from groundwater to heat pump system (kW)
$Q_{h,tot}$	total heat pump output to the heating system during a heating-season (kWh/year)
T	temperature (K)
ΔT	heating water mean temperature and indoor temperature difference (K)
W_{tot}	total energy consumption of the heat pump during a heating-season (kWh/year)

Greek symbols

ε	thermodynamic perfect degree
η	exergy efficiency ratio
τ	participation of ambient temperature interval in a heating season duration [%]

Subscripts

a	ambient (outside air)
gw	groundwater
id	indoor (heated space)
sys	system

[11] who have conducted a comparative exergetic assessment of two ground source heat pump systems for residential applications. Bi et al. [12] have presented a comprehensive exergy analysis of three circuits and whole system of a ground-source heat pump for both building heating and cooling modes.

Considering the ways of improving efficiency of the heat pumps operating by relatively large temperature differences Wang [13] and Wang et al. [14] have proposed two-stage heat pump system with vapor-injected scroll compressor, and Goricanec et al. [15] and Antonijevic and Komatina [16] suggested utilization two-stage cascade heat pump systems in high temperature heating applications.

2. Analyzed heat pump layouts

The performance and efficiency of a groundwater heat pump used in high temperature water heating systems are characterized by the type of vapor compression cycle, properties of underground water (temperature, flow and chemical composition) and seasonal ambient conditions. The selection of type of heat pump vapor compression cycle, optimized for a specified location, is crucial for energy and economy efficient and reliable operation of the heating system. For a selected location in New Belgrade Municipality, where substitution of fossil fuel high-temperature central heating by groundwater heat pump system has been planned, the energy and exergy analysis of possible heat pump system layouts has been undertaken, aiming to find the optimal cycle for the location dependent set of boundary conditions.

The following heat pump vapor compression cycles has been analyzed:

1. One-stage conventional heat pump cycle (used as baseline) (Fig. 1)
2. Two-stage cycle with external intercooling (Fig. 2)
3. Two-stage cycle with refrigerant injection (Fig. 3)
4. Two-stage cycle with refrigerant injection and internal heat exchanger (Fig. 4)
5. Two-stage cycle with vapor injection and flash tank (Fig. 5)
6. Cascade two-stage cycle (Fig. 6)

2.1. Energy analysis

The main parameter in energy performance analysis of a heat pump system is Coefficient of Performance (COP), defined as ratio of thermal power supplied to the heating system to the power consumed by the heat pump:

$$\mathrm{COP} = \frac{\dot{Q}_h}{P} \tag{1}$$

Since COP is dependent on boundary conditions (T_{gw}, T_a, T_{id}, etc.), it is favorable to observe it over the course of an average heating-season as Seasonal Coefficient of Performance ($\mathrm{COP}_{seasonal}$), calculated as ratio of total heating output (to the heating system) during a typical heating season to total compressor(s) work input during the same period:

$$\mathrm{COP}_{seasonal} = \frac{Q_{h,tot}}{W_{tot}} \tag{2}$$

For an existing building, with certain thermal properties, energy required for heating depends mainly on outside air temperature, wind speed and desired indoor temperature. The relation between outside air temperature and hot water supply and return temperatures, for the existing buildings at the selected location, is defined by diagram (Fig. 7) based on data acquired from district heating supplier (Public Utility Company Belgrade Heating Plants) [17]. The variability of ambient conditions is taken into account through outside air temperature and the delivered heat load is regulated by hot water supply temperature.

For cast iron radiators, used in the building, total heat transferred from radiators to heated space can be determined as in [18]:

$$\dot{Q}_h = \dot{Q}_{h,n} \cdot \left(\frac{\Delta T}{60}\right)^{4/3} \tag{3}$$

Using data defining heating regimes (Fig. 7) and Eq. (3), for the heating system operating in a steady state regime the heating load can be defined as a function of outdoor temperature: $\dot{Q}_h(T_a)$. Regarding that groundwater temperature and refrigerant evaporation temperature are constant, all the variables in coefficient of performance calculation (pressure ratios, compressors efficiencies) depend solely on refrigerant condensation temperature, which is determined by thermal load dictated by actual ambient condition. Therefore COP can be expressed as a function of outdoor temperature: $\mathrm{COP}(T_a)$.

To determine the amount heat supplied to the heating system during a whole heating season, it is necessary to statistically estimate outside air temperature frequency distribution function for a typical heating season. For the selected location in Belgrade, hourly readings of temperatures during 24 heating seasons (years 1985–2009) were taken to account. In average, there were 4277 heating hours per heating season. Share of days with daily outside air temperature below 0 °C was 18% and the lowest recorded daily outside air temperature was −11.3 °C. The frequency distribution of the outside air temperature is shown in Fig. 8. Single points represent temperature interval of 1 °C.

Using a rational function with estimated coefficients (a_i, i = 1,. . ., n) to fit the empirical weather data (Fig. 8.), the duration of infinitesimal outside air temperature interval, in percentage of duration of typical heating season, can be expressed as:

$$d\tau(T_a) = \frac{a_1 + a_2 T_a}{1 + a_3 T_a + a_4 T_a^2} dT_a \quad (\%) \tag{4}$$