Energy and Buildings 42 (2010) 1987–1994

Contents lists available at ScienceDirect

Energy and Buildings

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

Exergetic cost analysis of a space heating system

Xiang Jingyan[a,b,*], Zhao Jun[a], Qin Na[a]

[a] *School of Mechanical Engineering, Tianjin University, Tianjin 300072, China*
[b] *Shenyang Institute of Engineering, Shenyang 110136, China*

ARTICLE INFO

Article history:
Received 10 October 2009
Received in revised form 5 May 2010
Accepted 13 June 2010

Keywords:
Groundwater source heat pump
Thermoeconomics
Structural theory
Exergetic cost

ABSTRACT

In order to evaluate and improve the design of space heating systems with groundwater source heat pumps (GWHP), common design practices should be examined. In this paper, a GWHP system with common design is studied. The *COP* of the heat pump is 3.5 at design condition. The system is divided into five subsystems, and exergetic cost analysis is performed on it based on structural theory of thermoeconomics. The results show that the three largest relative exergy destructions and lowest exergy efficiencies occur in power generation and distribution, heat pump, and terminal unit subsystems with relative exergy destructions of 71.2%, 17.1% and 7.02% and exergy efficiencies of 32.8%, 54.8% and 65.6% respectively. The three subsystems also have the largest increases of unit exergetic costs of 2.04 W/W, 2.15 W/W, and 2.73 W/W respectively. Therefore, designers of GWHP space heating systems should pay close attention to heat pump and terminal unit subsystems, especially to the latter one because of its larger increase of unit exergetic cost. The unit exergetic cost of the system final exergetic product is 7.92 W/W. This value can be used to evaluate the system and compare it with others from the viewpoint of energy conservation.

1. Introduction

With the growing concern about energy conservation, environmental protection, and sustainable development, the analysis and evaluation of space heating systems is getting more and more important. In Shenyang city of China, space heating and air conditioning systems with GWHP are developing rapidly, so the analysis and evaluation of their performances is crucial for their proper design, operation and management.

Energy analysis is commonly used for the analysis of energy systems because of its simplicity. However, it fails to reveal some kinds of loss because it only considers the quantity of energy. The quality of energy is also very important in this area. In winter, room temperature needs to be maintained at only about 20 °C, so the energy quality of the heating load is low. The concept of low temperature heating and high temperature cooling and low exergy systems for the heating and cooling of buildings have been proposed in IEA ECBCS Annex 37 [1]. In order to detect true losses in heating and cooling systems and make improvement, exergy analysis for whole energy chains—from primary energy source, via buildings, to sinks (i.e. the ambient environment)—has been applied.

Schmidt [2] presented a pre-design tool, which had been produced during the work for the IEA ECBCS Annex 37, to perform energy and exergy analysis to building heating systems. All steps of the energy chain were included in the analysis. The tool was aimed at calculations under steady state design condition, not at annual energy use calculations. With the help of the tool he made a comparison of different design options including liquefied natural gas (LNG) fired high temperature boiler, LNG condensing boiler, ground-source heat pump, direct electrical heating with convectors, low temperature floor heating, higher insulation standard, and balanced ventilation system with heat recovery. Based on the tool, Balta et al. [3] performed an exergy analysis of a low exergy heating system for a room from the power plant through the ground-source heat pump to the building envelope. The *COP* of the heat pump was 2.32. Indoor and exterior air temperatures were 20 °C and −15 °C, respectively. They quantified and illustrated exergy destructions in the overall system. With the help of the same tool, Yildiz and Güngör [4] presented energy and exergy analysis for the whole process of the space heating of an office. An LNG conventional boiler, an LNG condensing boiler and an external air–air heat pump were considered as the heat sources. The *COP* of the heat pump was 3.2. Indoor and exterior air temperatures were 20 °C and 0 °C, respectively. They quantified and illustrated exergy destructions in the overall systems. They also compared the exergy efficiencies of the three systems.

The authors mentioned above all adopted one reference dead state to perform exergy analysis. Ozgener et al. [5] investigated

---

[*] Corresponding author at: Shenyang Institute of Engineering, Shenyang 110136, China. Tel.: +86 24 31975537; fax: +86 24 31975537.
E-mail address: cinaxiangjy@hotmail.com (J. Xiang).

0378-7788/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2010.06.004

Nomenclature

AC	air exchange rate (ach/h)
a	coefficient
b	national average consumption rate of standard coal for power production and distribution (g/kWh)
c_p	specific heat (kJ/(kg °C))
COP	coefficient of performance of heat pump
$\dot{E}$	exergy rate (kW)
EHR	ratio of electricity consumption to heat transferred
$\dot{E}n$	primary energy consumption rate (kW)
$F_{q,load}$	quality factor of heating load
$\dot{F}$	exergetic fuel rate (kW)
h'	storey height (m)
h	specific enthalpy (kJ/kg)
H	well pump head (m)
H_d	low heating value of standard coal (kJ/kg)
$\dot{I}$	exergy destruction rate (kW)
k	unit exergy consumption
k^*	unit exergetic cost (W/W)
$\dot{m}$	mass flow rate (kg/s)
n	number of subsystems
$\dot{P}$	exergetic product rate (kW)
$\dot{Q}$	heating load of buildings (kW)
R_{HL}	heat loss rate of heat distribution network
s	specific entropy (kJ/(kg K))
S	shape coefficient of buildings
T	temperature (K)
U	average overall heat transfer coefficient of building envelope (W/(m^2 K))

Greek letters

η	efficiency
ρ	density (kg/m^3)
χ	relative exergy destruction
δ	fuel depletion rate
Δ	increment
$\sum L$	total length of main pipes (m)

Subscripts

0	external source or reference state
a	air
ex	exergy
F	exergetic fuel
i	indoor
i, j	index for numerating subsystems or flows
o	outdoor
P	exergetic product
tot	total of the whole system
w	water
$w1$	water leaving production well
$w2$	water entering reinjection well
ws	supply water of heat pump
wr	return water of heat pump
wp	well pump

how varying reference temperature from 0 °C to 25 °C would affect the energy and exergy efficiencies of the Balcova geothermal district heating system and developed two significant correlations that could be used for predicting the efficiencies. Angelotti et al. [6] adopted time dependent outdoor temperature as reference temperature, and carried out a dynamic evaluation of the exergy efficiency of a reversible air source heat pump providing heating and cooling to a simple building, and compared the dynamic results to those obtained from three different reference temperatures.

Through exergy analysis, irreversibility or exergy destruction in a system can be revealed and quantified. For system improvement, efforts should be made to decrease exergy destruction. However it is better for us to know which decreases of exergy destructions are more important for system improvement.

With the development of thermoeconomics, it has been realized that variation of irreversibility in different parts of a system has different impacts on the energy consumption of the system, which is known as principle of technical non-equivalence of the local irreversibility [7,8]. This principle reflects an interesting character of exergy destruction, and it has been applied to the thermoeconomic diagnosis of power systems. The non-equivalence of the local irreversibility is shown with different unit exergetic costs. Valero et al. [9] demonstrated the application of unit exergetic costs to the thermoeconomic diagnosis of a conventional coal-fired power plant by applying structural theory of thermoeconomics. Verda [8] studied thermoeconomic diagnosis of an urban district heating system based on cogenerative steam and gas turbines by use of unit exergetic costs and structural theory of thermoeconomics. In the diagnosis, unit exergetic costs have shown a powerful role in determining the effects of the local increase of exergy destruction caused by malfunction on the total exergetic fuel of a system. However, for system improvement, we are interested in the effects of the local decrease of exergy destruction on the total exergetic fuel of a system. Therefore unit exergetic costs may also be helpful to the analysis and improvement of systems. Xiang et al. [10] have carried out an exergetic cost analysis for a pressurized internal reforming solid oxide fuel cell plant and evaluated the design of the plant.

This paper applies unit exergetic costs and structural theory of thermoeconomics to a commonly designed space heating system with groundwater source heat pumps in Shenyang city of China. The purpose is to investigate the utilization of unit exergetic costs to analyze and evaluate GWHP systems. In the analysis, unit exergetic costs as well as exergy destructions and exergy efficiencies at design condition are calculated at the same time. The results are then used to give suggestions to system improvement.

2. System description

The space heating system with GWHP is located in Shenyang city of China. It supplies heat to four residential buildings with total building area of 30,000 m^2. Radiant floor heating is used in the system. A schematic diagram of the system is shown in Fig. 1. The well water is drawn by the well pumps through the heat pump. After rejecting heat to the heat pump, it returns to the reinjection wells. The heat pump receives heat from the well water, and rejects heat to the circulating water. The heated circulating water is then pumped to the buildings to supply heat.

3. Analysis

3.1. Analysis method based on structural theory of thermoeconomics

The GWHP system from the power plant to the rooms can be divided into five subsystems, which are respectively power generation and distribution, well water transportation, heat pump, heat distribution, and terminal unit subsystems, as illustrated in Fig. 2. In structural theory of thermoeconomics, Fig. 2 is called physical structure of the system [11].

For analysis, besides physical structure, a productive structure of the system is also needed, which shows all the subsystems and their functions of providing exergetic product at the expense of