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Theoretical analysis on ground source heat pump and air source heat pump systems by the concepts of cool and warm exergy

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ABSTRACT

This study presents exergetic characteristics of both ground source heat pump systems (GSHPs) and air source heat pump systems (ASHPs) based on the concepts of "cool exergy" and "warm exergy". Quantitative example followed by theoretical analysis shows that GSHPs consume less exergy than ASHPs do. This is because firstly "cool exergy" is obtained from the ground in GSHPs, whereas no "cool exergy" is extracted from the environment by the ASHPs. Secondly, temperature difference between refrigerant via cooling water and ground in GSHPs is smaller than that between refrigerant and air in ASHPs. In the GSHP, cool exergy flows into the cooling water from the ground and then enters the indoor air through the refrigerant cycle. In the ASHP, the refrigerant cycle separates the electricity input of the compressor into "cool exergy" and "warm exergy." The "cool exergy" enters the indoor air and the "warm exergy" is exhausted to the ambient environment. The analysis also shows that compressor requires largest exergy input among the total exergy inputs, and the exergy consumption in the refrigerant cycle is the highest. Thus, the improvement of the compressor performance to reduce its electricity consumption was confirmed to be of vital in minimizing unnecessary exergy consumption.

1. Introduction

For evaluating an energy-related system, the quality of the energy inflow and outflow at any point in the system can be determined using the concept of exergy. Exergy is a portion of energy that can be utilized for work relative to a reference state condition, in which the exergy value is zero. The exergy method shows the real change in the work of the system, process by process. This is the exergy concept presented by Ahern [1]. Exergy analysis has been applied to many fields of engineering and science, such as mechanical engineering for optimization of power plants and cogeneration stations, and food engineering for analyzing processing operations [2]. Several studies have demonstrated the applicability of the exergy concept to heating and cooling systems [3–7]. These studies have shown potential ways to improve system energy and exergy performance, e.g., lowering supply air temperatures [3] and improving insulation of the building envelope [4] to increase the exergy efficiency of the system.

Heat pump systems, especially GSHPs have been widely used on account of their high energy performance, and the installed capacity has increased dramatically over the last 15 years [8,9]. Some studies have applied the exergy concept to GSHPs [10–12]. However, these studies have not dealt with warmth and coolness in the built environment, which are relative to "warm exergy" and "cool exergy" [6,7]. In order to evaluate the system performance and indoor thermal comfort, it is necessary to apply the "warm exergy" and "cool exergy" concepts.

In this paper, based on "warm exergy" and "cool exergy", exergy flow pattern from heat pump systems to indoor air is demonstrated for a better understanding of heat pump systems leading to such a development of low exergy systems. On the basis of energy, entropy, and exergy balance equations, the entropy and exergy processes of heat pump systems are presented, and a mathematical model including exergy supply, exergy consumption, entropy generation and entropy disposal for each component is demonstrated. Furthermore, a case study is presented, where this model is used for both a GSHP and an ASHP. The exergy consumptions and exergy efficiencies of these two systems are calculated, and the potential for improvement is discussed.

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Nomenclature

List of symbols

E_{comp}	compressor power [kW]
$E_{fan,ia}$	indoor fan power [kW]
E_{pump}	power of cooling water pump [kW]
$E_{fan,oa}$	outdoor fan power [kW]
Q_e	energy flux between indoor air and refrigerant in the evaporator [kW]
Q_c	energy flux between refrigerant and cooling water or outdoor air [kW]
Q_g	energy flux between ground and cooling water [kW]
$Q_{c,GS}$	energy flux between refrigerant and cooling water in GSHP systems [kW]
$Q_{c,\ AS}$	energy flux between refrigerant and outdoor air in ASHP systems [kW]
T_o	outdoor temperature [K]
T_g	average ground temperature [K]
T_e	refrigerant evaporation temperature [K]
T_c	refrigerant condensation temperature [K]
T_{ia}	indoor air temperature [K]
$T_{ia,\mathrm{sup}}$	supply air temperature [K]
T_w	cooling water temperature [K]
$T_{w,re}$	return water temperature [K]
$T_{oa,out}$	outlet air temperature of condenser heat exchanger of ASHP [kW]
$T_{c,GS}$	refrigerant condensing temperature of GSHP [K]
$T_{c,AS}$	refrigerant condensing temperature of ASHP [K]
$\Delta T_{o-c,AS}$	temperature difference between $T_{c,AS}$ and the ambient temperature T_o [K]
ΔT_{ia-e}	difference between refrigerant evaporating temperature and indoor air temperature [K]
ΔT_{w-g}	temperature difference between ground and cooling water [K]
$\Delta T_{c,GS-w}$	difference between cooling water temperature and refrigerant condensing temperature [K]
X_e	output exergy from the refrigerant to the indoor air at the evaporator [kW]
$X_{c,GS}$	output exergy from the refrigerant to the cooling water of GSHP systems [kW]
$X_{c,AS}$	output exergy from the refrigerant to the outdoor air of ASHP systems [kW]
X_g	exergy extracted from ground and delivered to cooling water [kW]
$X_{ia,\mathrm{sup}}$	supply air exergy [kW]
X_{ia}	return air exergy [kW]
X_w	cooling water exergy [kW]
$X_{w,re}$	return cooling water exergy [kW]
X_o	exergy contained by ambient air (=0) [kW]
$X_{oa,out}$	outlet air exergy of outdoor fan [kW]
$X_{refcycle}$	exergy consumed in the refrigerant cycle [kW]
X_{evap}	exergy consumed in the heat exchanging process between indoor air and the refrigerant [kW]
$X_{cond,GS}$	exergy consumed in the heat exchanging process between the cooling water and the refrigerant [kW]
$X_{cond,AS}$	exergy consumed in the heat exchanging process between outdoor air and condenser [kW]
X_{gex}	exergy consumed in the heat exchanging process between cooling water and ground [kW]
$S_{refcycle}$	entropy generated in the refrigerant cycle [kW/K]
S_{evap}	entropy generated in the heat exchanging process between indoor air and the refrigerant [kW/K]
$S_{cond,GS}$	entropy generated in the heat exchanging process between the cooling water and the refrigerant [kW/K]
$S_{cond,AS}$	entropy generated in the heat exchanging process between the outdoor air and the refrigerant [kW/K]
S_{gex}	entropy generated in the heat exchanging process between cooling water and ground [kW/K]
m_{ia}	indoor fan airflow rate [kg/s]
m_w	cooling water flow rate [kg/s]
m_{oa}	outdoor airflow rate [kg/s]
c_a	specific heat capacity of air [kJ/kgK]
c_w	specific heat capacity of water [kJ/kgK]
k	irreversibility factor (the ratio of actual COP to theoretical COP)
l_1	circumference of pipe cross section [m]
l_2	pipe length [m]
U	overall heat-transfer coefficient of underground heat-exchanger pipe [W/m^{2}K]

2. Basic theory

According to Shukuya [6,7], in a system at a temperature higher than its environment, exergy flow can be considered as the flow of thermal energy contained by the system to disperse into the environment. This exergy is called "warm exergy" flow. It is shown in Fig. 1(a). In the figure, the environment temperature T_o acts as the cold reservoir and heat Q is extracted from the hot reservoir with temperature T. The exergy flow E_x is exactly the same as the maximum amount of work $W_{\max}$ to be obtained from an imaginary reversible perfect heat engine.

$$E_x = W_{\max} = \frac{1 - T_o}{T} Q \tag{1}$$

If the system temperature is lower than the ambient temperature, then the thermal energy contained by the system is smaller than the environment. Because of this, heat flows into the system from the environment. The exergy flow in this condition is "cool exergy". Fig. 1(b) illustrates the definition of "cool exergy" flow. The equation for "cool exergy" is

$$E_x = W_{\max} = \frac{1 - T_o}{T} (-Q^*) \tag{2}$$

Exergy balance equations are obtained from energy and entropy balance equations [6,7]. First, following the laws of energy conservation and entropy generation, energy balance equations and entropy balance equations are set up in a general form as

$$[\text{energy input}] = [\text{energy stored}] + [\text{energy output}] \tag{3}$$

(a) Definition of "warm exergy", T > To **(b) Definition of "cool exergy", T < To**

Fig. 1. Definition of "warm exergy" and "cool exergy".