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Optimal operation strategy of the hybrid heating system composed of centrifugal heat pumps and gas boilers

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ABSTRACT

Centrifugal heat pump has to be coupled with gas boiler to supply high temperature water in radiator heating system. Regarding to hybrid heating system (HHS), operation strategy has significant impact on its annual energy consumption and cost. In this paper, the optimal operation strategy of the HHS composed of sewage-source centrifugal heat pumps and gas boilers was analyzed. Firstly, the performance models of the system components, including terminal radiator, heat pump, gas boiler and water pump were established respectively. Secondly, with the aim at minimizing the operating cost of the system the optimal operation strategy of the system was analyzed. Finally, the annual operating cost and energy consumption of the HHS were compared with these of coal-fired boiler heating system. The results indicate that the HHS offers significant reductions in energy consumption (45.2%) and operating cost (13.5%). Therefore, the HHS has a promising application prospect, the results provide reference for scientific operation of the HHS.

1. Introduction

China's rapid economic growth is inevitably accompanied by serious environmental problems, such as pollution, energy shortage and climate change [1]. In China, approximately 27.8% of the primary energy is consumed in non-industrial buildings [2]. In Northern China, 36% of the total building energy consumption is utilized for heating in urban areas [3]. Efficient energy use is considered to be a solution of addressing fossil fuel depletion, energy security, and global warming [4].

Using heat pump to recover waste heat is of great significance in energy saving and environmental protection [5], sewage source heat pump (SSHP) heating system is now considered as a viable alternative to conventional heating system. Many studies have been conducted on SSHP heating system. Shen et al. [6] studied the influence of a novel evaporator with defouling function on the performance of a SSHP. Zhao et al. [7] searched for suitable method to improve the performance of a SSHP system. Li et al. [8] studied the feasibility of using low-grade heat for thermal desalination via a hybrid absorption heat pump system. Baek et al. [9] investigated the feasibility of the waste water use for heat pump as heat source. Kahraman et al. [10] analyzed the impact of the heat source temperature on the energy performance of a SSHP system. Liu et al. [11] analyzed the advantage of a SSHP system used in public shower facilities. Tassou [12] presented a simple methodology for sizing and performance analysis of heat pump systems in sewage effluent heat recovery applications. Li et al. [13] studied the economics and environmental protection value of a SSHP. Funamizu et al. [14] introduced some SSHP systems in Japan. Wu et al. [15–17] put forward a hydraulic reactive method to wash the soft-dirt in heat-exchanging pipe, performed the technical and economic analysis of the increase in heat pump temperature in the sewage disposal process, and reviewed the utilization progress of intake water heat-exchange technique of SSHP systems. Qian et al. [18] analyzed the effect of flow rate on energy consumption and economical efficiency of the SSHP system.

In order to further improve the energy efficiency and decrease the initial cost of heat pump heating system, heat pump is often coupled with conventional heating equipments, and many studies have been conducted on this type of hybrid heating system (HHS). Scarpa et al. [19] simulated the performance of the HHS composed of heat pump and gas boiler. Blarke and Dotzauer [20] found the HHS composed of heat pump and CHP (combined heat and power) offers significant reductions in fuel consumption and operational costs. Pardo et al. [21] studied the energy efficiency improvement of the HHS composed of heat pump and thermal storage. Yavuzturk and Spitler [22], Xu [23] and Hackel and Pertzborn [24] studied the performance of HHSs in reducing the thermal imbalance of the soil, in these HHSs, ground-source heat pump is combined with cooling tower [22,23] or gas boiler [24].

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Nomenclature

Q	heating load of the buildings (kW)
K	heat transfer coefficient (kW/(m^2 K))
F	area (m^2)
t	temperature (°C)
G	volume flow rate (m^3/h)
c_p	specific heat of water (kJ/(kg K))
x	load ratio
E	input power (kW)
q	lower heating value (kJ/kg)
m	the number of gas boiler
H	pump lift (m)
k	speed ratio of pump
H_0	hydrostatic head (m)
S	pipe impedance (s^2 m^{-5})
abc	correction coefficient
c	operating cost (Yuan)
P	price (Yuan)
n	frequency (day)
M	coal consumption (kg/h)
e	electricity consumption rate of coal-fired boiler (kWh/t)

Greek symbols

η	efficiency
γ	specific weight (9.807 kN/m^3)
η_t	delivery efficiency of the power network

Subscripts

in	indoor
a	outdoor mean temperature
d	design condition
i	inlet
R	radiator
o	outlet
sys	system
DL	distribution loss
fl	full load condition
c	condenser
e	evaporator
pl	part load condition
h	heat pump
gb	gas boiler
g	gas
au	auxiliary equipments
p	pump
m	motor
v	variable frequency driver
cp	circulation pump
sp	sewage pump
elc	electricity
min	minimum
j	different operation modes of the system
max	maximum
k	different outdoor temperature
co	coal
b	coal boiler

Abbreviations

SSHP	sewage source heat pump
HHS	hybrid heating system
COP	coefficient of performance
OCSR	operating cost savings ratio
ESF	energy saving factor
REPI	relative energy price index

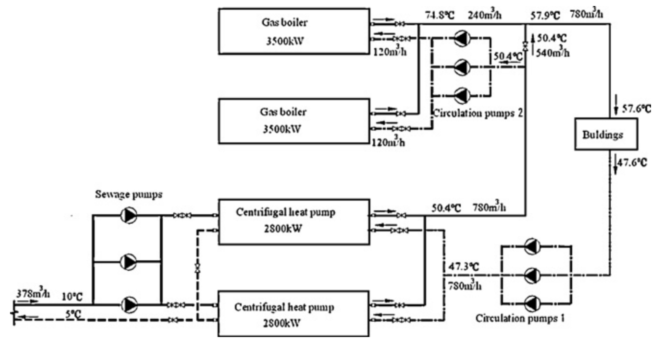

Fig. 1. Flow chart of the hybrid heating system.

From the above literatures, studies on SSHP systems and HHSs mostly focus on system design, energy performance and economic assessment. To the best of the authors' knowledge, operation strategy of HHS has not previously been analyzed. In addition, the literature mainly focuses on the HHS composed of sewage source centrifugal heat pumps and gas boilers. As the terminal of the heating system is radiator, the design supply water temperature is higher than the outlet water temperature of condenser, cascade mode between heat pumps and gas boilers is an attractive solution to meet the need of radiators. To reduce the operating cost and improve the energy efficiency of a HHS, operation strategy is required.

For HHS, the mismatch between the heating load of the system and heat output of each heating equipment at different outdoor temperatures, the outlet water temperature setting for each heating equipment at different outdoor temperatures are the two main problems. To solve these problems, operation strategy of the HHS at different outdoor temperatures should be studied. The main purpose of this study is to propose a scientific, reasonable and feasible optimization control method for the HHS.

2. HHS overview

This HHS is applied in a residential community in Xi'an, China. The residential community is composed of residential buildings (of 228,760 m^2 floor area with heating load index of 37 W/m^2) and public buildings (of 11,215 m^2 floor area with heating load index of 50 W/m^2).

In this case study, the terminal of the heating system is radiator. Sewage source centrifugal heat pump is adopted to afford the basic heating load of the system. At the design condition, the supply water temperature of the system is 57.9 °C, the highest outlet water temperature of the centrifugal heat pump is 51 °C, which is lower than the design supply water temperature of the system. Therefore, gas boilers are deployed for regulating the supply water temperature and peak load compensation. In order to improve the energy efficiency of the system, the cascade mode is adopted between sewage source centrifugal heat pumps and gas boilers in the system. The flow chart of the HHS is shown in Fig. 1.

At the design condition, the return water of the HHS is first heated in the heat pump condenser, then part of the outlet water from the condenser flows into the gas boilers, and the outlet water from the gas boiler is mixed with the rest of the outlet water from the condenser, finally, the mixed water is supplied to buildings. For sewage system, in order to prevent freezing in evaporator, the minimum outlet water temperature is set at 5 °C.

The major energy consuming equipments in the HHS are heat pumps, gas boilers, sewage pumps, circulation pumps and electrical auxiliary equipments of gas boilers. The parameters of these equipments are shown in Table 1.