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A new utilization approach of the waste heat with mid-low temperature in the combined heating and power system integrating heat pump

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HIGHLIGHTS

- A new utilization approach of the waste heat with mid-low temperature is presented.
- A new CHP–GSHP coupling system is proposed to explain the integrating mechanism.
- The performances of the new CHP–GSHP coupling system are numerically investigated.
- The superiorities of the proposed system are demonstrated.

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ABSTRACT

The efficient utilization of the waste heat with mid-low temperature from the combined heating and power (CHP) system is crucial for the improvement of the energy efficiency. In the CHP system, the waste heat with mid-low temperature was directly used to generate domestic hot water or heat by the heat exchanger. Different from common methods, in this paper a new utilization approach of the waste heat with mid-low temperature by integrating the CHP system and the ground source heat pump (GSHP) was proposed, and a new coupling system was designed based on the integrating mechanism. Numerical simulations were implemented to investigate the performances of the proposed coupling system. The influence characteristics of the temperature of the warm water generated by the GSHP on system performances, including the coefficient of performance (COP) of the GSHP, the heat output and the total energy efficiency, were revealed. The results showed that with the same input and heat output, the proposed system can generate more power than the reference system, and the total energy efficiency and the COP of the GSHP were simultaneously improved.

1. Introduction

In recent years, new energy generation systems, such as the combined cooling, heating and power (CCHP) systems and the CHP systems, have attracted increasing attention. The CCHP or the CHP is more efficient, economical and environmental friendly than traditional energy systems [1–5]. In such systems, the efficient utilization of the waste heat with mid-low temperature discharged from the prime mover is very crucial for the improvement of the energy efficiency.

According to the principle of the temperature counterparts and energy cascade utilization, the waste heat usage technologies applied in CCHP or CHP are various. Saidur et al. [6] and Hatami et al. [7] had done a review on this issue. These technologies include the thermoelectric generators, the organic Rankine cycle, the six stroke engines, the turbocharging, the exhaust gas recirculation, the exhaust heat exchanger (HEX), etc. In CCHP or CHP, the waste heat with mid-low temperature (it generally refers to flue gas) is mainly used by the HEX to produce heat or generate domestic hot water directly [1–5]. Due to the wide applications of the waste heat with mid-low temperature by the HEX, the improvement of the heat transfer efficiency via the special design of the HEX structure is crucial for the efficient utilization of the waste heat with mid-low temperature [8,9].

In some areas, the waste heat with mid-low temperature is always used to supply heat or domestic hot water by the HEX directly for the heat recovery. However, the waste heat often cannot meet the requirement of the building heat. The additional heat needs to be generated by other equipment or system, such as heat pump (HP). As a result, it is vital to find an efficient system integrating method to utilize the waste heat with mid-low

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Nomenclature

Abbreviations

CCHP	combined cooling, heating and power
CHP	combined heating and power
HEX	heat exchanger
HP	heat pump
GSHP	ground source heat pump system
COP	coefficient of performance
NTU	number of transfer units
A	surface area, m^2
U	heat transfer coefficient, $W/m^2 \cdot °C$
C_c	heat capacity of the cold fluid, J/°C
C_h	heat capacity of the hot fluid, J/°C
C_{min}	$\min[C_c, C_h]$
C_{max}	$\max[C_c, C_h]$
T	hot fluid temperature, °C
t	cold fluid temperature, °C
ΔT_{min}	$\min[T_i - T_o, t_o - t_i]$
ΔT_{max}	$\max[T_i - T_o, t_o - t_i]$
C_p	specific heat at constant pressure, J/kg·°C
m	mass flow, kg/s
T_{ci}	inlet temperature at condenser side, °C
T_{co}	outlet temperature at condenser side, °C
T_{ei}	inlet temperature at evaporator side, °C
T_{eo}	outlet temperature at evaporator side, °C
ΔT_{em}	mean temperature difference of evaporator, °C
ΔT_{cm}	mean temperature difference of condenser, °C
T_w	temperature of the warm water, °C
q_h	amount of heat transfer in HEX, J
w	power consumption of unit mass refrigerant, kW
R'	universal constant
n	polytropic exponent
q	heating generation per unit mass refrigerant, kW
p	pressure, kPa
Q	heat, kW
W	power, kW

Greek symbols

ε	HEX efficiency
η	total energy efficiency, %

Subscripts

i	inlet
o	outlet
e	evaporator
c	condenser
w	warm water

temperature and improve the system performances. The common integrating methods can be approximately divided into three categories: (1) the waste heat with mid-low temperature is treated as a heat source of the HP [10–13]. The method can improve the COP of the HP, but fail to increase the additional heat output; (2) the heat systems are operated in a parallel mode [12,14–18]; in other words, the both systems are operating independently. The integrating way can only increase the heat output, and (3) the waste heat with mid-low temperature is used to reheat the outlet stream of the HP at the condenser side to achieve the required temperature [12,13,19]. The method can prevent the decrease of the COP of the HP by means of the system integrating way, but the advantage of the energy saving should be exploited. It is worth mentioning that, due to the large temperature difference of heat transfer between the hot and cold fluids, the utilization efficiency of the waste heat with mid-low temperature based on the heat transfer mechanism of the HEX is low, and the total energy efficiency of systems should be improved. For the utilization of the waste heat with mid-low temperature by the HEX, the HEX efficiency will change with the variations of the inlet temperature of the cold fluid according to the heat transfer characteristics [20]. For the HP, the COP is mainly subject to the outlet stream temperature at the condenser side when the HP unit has been set up [21–23]. Therefore, the changes of the utilization approach of the waste heat with mid-low temperature may improve the total energy efficiency.

In order to make a better use of waste heat with mid-low temperature, a new integrating mechanism for the utilization of the waste heat with mid-low temperature will be presented in detail. Then, based on the integrating mechanism, a new coupling system is proposed, which integrates the CHP system and the ground source heat pump (GSHP). Finally, a case system is given to verify the performance advantages; Moreover, the thermodynamic performances and the influence characteristics of the key operating parameter on the proposed system are also numerically investigated.

The rest of this paper is organized as follows. In Section 2, a new coupling system is proposed based on the CHP and GSHP, and the reference system is also given for a comparison. In Section 3, the HEX efficiency, the HP mechanism and the system integrating mechanism are introduced. In Section 4, the thermodynamic performances and the influence characteristics of the key operating parameter are numerically investigated. In Section 5, main conclusions are summarized.

2. CHP–GSHP coupling system

In order to illustrate the new utilization approach in details, a new coupling system that integrates the CHP system and the GSHP is proposed firstly, which is shown in Fig. 2. At the same time, a common CHP–GSHP coupling system is given in Fig. 1 as a reference system. It should be pointed out that the major difference of the both systems depends on the utilization approach of the waste heat with mid-low temperature from the CHP. The above systems were reported in Ref. [24], in which the gas turbine is selected as the prime mover of case system. Although, the analysis in this paper focuses mainly on the utilization approach of the waste heat with mid-low temperature, the selection for the prime movers is also very crucial. It should be based on the characteristic of prime mover itself, and consider simultaneously the user's load demand and the factor of environment and economy etc aspect. The size of the internal combustion engines can range from 10 kW to over 5 MW; Considering the advantages of low capital cost, quick starting, well load following, relatively high partial load efficiency and generally high reliability, the internal combustion engines can be also selected as the prime movers [25]. The size of gas turbines ranges from 500 kW to 250 MW; it can be selected as the prime movers when considering its merits of compact and flexible design, low GHG emissions, low maintenance levels, high-quality exhaust heat; Moreover, it is more suitable to be applied in the huge amount of thermal demand areas [25].

It can be observed from Fig. 1 that, the compressed natural gas and air will be sent into combustor, after combustion the flue gas with the high temperature (1040 °C) and high pressure (13 atm)