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Research paper

Simulation of a heat pump system for total heat recovery from flue gas

Maolin Wei [a], Weixing Yuan [a,*], Zhijia Song [a], Lin Fu [b,*], Shigang Zhang [b]

[a] Laboratory of Ergonomics and Environmental Control, School of Aeronautic Science and Engineering, Beijing University of Aeronautics and Astronautics, 37 Xueyuan Road, Beijing, 100191, China
[b] Dept. of Energy Planning and Design, Tsinghua University, 30 Shuangqing Road, Beijing, 100084, China

HIGHLIGHTS

- An OAHP system is analyzed to improve heat recovery from natural gas flue gas.
- OAHP system models are presented and analyzed.
- The key factors influencing the OAHP systems are analyzed.
- The OAHP system is most efficient for most cases compared with other systems.
- The OAHP system is more economic than other systems.

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ABSTRACT

This paper introduces an approach of using an open-cycle absorption heat pump (OAHP) for recovering waste heat from the flue gas of a gas boiler with a system model. And equivalent energy efficiency is used to evaluate two other heat recovery systems that integrate an electric compression heat pump (EHP) or an absorption heat pump (AHP) with a boiler. The key factors influencing the systems are evaluated. The OAHP system efficiency is improved by 11% compared to the base case. And the OAHP system is more efficient than the AHP or the EHP systems, especially when the solution mass flow rate is only a little less than the cold water mass flow rate. The energy efficiency comparison is supplemented with a simplified economic analysis. The results indicate that the OAHP system is the best choice for the current prices of electricity and natural gas in Beijing.

1. Introduction

Natural gas-fired boilers are widely used due to their relatively high thermal efficiency and low emissions. Conventional boilers have thermal efficiencies of 70%–80%. Since the main species of natural gas is methane, which contains much hydrogen, methane combustion produces much water vapor in the flue gas, which carries a large amount of latent heat [1]. Recovery of the latent heat in the flue gas will significantly improve the natural gas boiler thermal efficiency.

Condensing boilers were developed for this purpose and have been used in many cases [2]. A condensing boiler contains a flue gas condenser installed at the flue gas exit of a boiler, with the flue gas cooled by the cooling media. A condensing boiler can be divided into the indirect heat exchanger type and direct-contact heat exchanger type depending on the condenser configuration. Liu [3] introduced a direct-contact heat exchanger for flue gas heat recovery and showed that a direct-contact heat exchanger had a higher heat transfer coefficient than an indirect one. However, both types of condensing boilers need a cooling fluid to cool the flue gas and in most cases, the gas boiler feed water is used. In district heating systems [4], the cooling water temperature is normally 40–60 °C, which limits the lower dew point of the flue gas. Thus the water vapor cannot be condensed completely and only a small part of the latent heat can be recovered. Therefore, the efficiency improvement by condensing boilers is very limited practically.

Besides condensing boiler, some studies have used heat pumps in heat recovery systems to use lower temperature cold sources to cool the flue gas. Hebenstreit et al. [5] evaluated an active condensation system for heat recovery from biomass boilers. The system used a compression heat pump to create cold water to cool the flue gas. Ming et al. [6] used an absorption heat pump (AHP) integrated with heat exchangers to recover the latent heat in boiler

* Corresponding authors. Tel.: +86 10 82338878.
E-mail address: yuanwx@buaa.edu.cn (W. Yuan).

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Nomenclature

COP	Coefficient of performance
d	Moisture content (g kg^{-1})
E	Electric power (kW)
F	area (m^2)
H	Enthalpy (kJ)
h	Enthalpy (kJ kg^{-1})
K	Mass transfer coefficient (kg m^{-2} s^{-1})
Le	Lewis number
m	Mass flow rate (kg s^{-1})
NTU	Number of transfer unit
n	Ratio
P	Pressure (kPa)
Q	Heat (kW)
Re	Reynold number
r	Latent heat of water (kJ kg^{-1})
Sc	Scott number
Sh	Sherwood number
T	temperature (°C)
V	Volume flow rate (m^3 s^{-1})
Z	Concentration of solution (g/g)
β	Gas price (RMB m^{-3})
γ	Electricity price (RMB kW^{-1} h^{-1})
η	Efficiency
¥	Cost (RMB)

Superscripts and subscripts

AHP	Absorption heat pump
abs	Absorber
cond	Condenser
cost	Cost
c	Concentrate solution
d	Dilute solution
EHP	Electric heat pump
e	Equilibrium
evap	Evaporator
flow-rate	Mass flow rate
g	Gas
gen	Generator
h	Heat exchanger
i	Inlet
m	Mass
max	Max
OAHP	Open-cycled absorption heat pump
o	Outlet
qmin	Minimum heat capacity.
recycle	Recycle
return	Return
s	Solution
sat	Saturation
supply	Supply
vap	Vapor
w	Water

flue gas. They introduced three configurations that improved the efficiency compared with a condensing boiler. The advantage of using a heat pump recycle the latent heat is to enable use of a low-temperature fluid. Thus, the system thermal efficiency is still limited by the temperature of the cold water that is used to cool the flue gas, since the latent heat is recovered through cooling by the cold water.

In addition to using a heat pump to create a low-temperature cold source, Riffat et al. [7] studied the feasibility of sorption systems for heat recovery. With better heat recovery by the sorption systems, Westerlund and Hermansson [8] used an open-cycle absorption heat pump (OAHP) system for heat recovery from a biomass boiler in experimental studies. Their results showed that the heat production was increased by 40% compared to an ordinary system when the bio-boiler was fired with wet biofuels.

The studies introduced above gave the performances of using heat pumps for heat recovery, but the performances comparisons of using different types of heat pumps were not involved. For OAHP, only experimental studies have been performed [8], and it is used for heat recovery from flue gas of a biomass boiler, which owns quite different composition with flue gas form gas boiler, for example, the humidity ratio is much higher. So in this paper, we introduce an approach to improve the thermal efficiency of natural gas boilers using the OAHP to recover the latent heat in the flue gas. This paper focuses on modeling the OAHP for heat recovery from a natural gas boiler. The OAHP system energy efficiency is compared with that of a condensing boiler and systems with a compression heat pump or an absorption heat pump. The results show that an OAHP system is more efficient in most cases.

2. OAHP heat recovery system

The OAHP system for flue gas heat recovery is shown in Fig. 1. Calcium chloride solution is used as the OAHP working fluid. When the system is running, flue damper 1 is closed and flue dampers 2 and 3 are open so that the flue gas will go into the absorber instead of the main flue tunnel. The external heat source for the generator is natural gas and its flue gas will also go into the absorber through flue damper 3 and be mixed with the flue gas from damper 2 before entering the absorber.

In the absorber, the solution is sprayed down and directly contacts the flue gas to absorb the water vapor in the flue gas. That is an exothermic process that increases the solution's temperature and reduces its concentration. Then, the dilute solution enters a solution heat exchanger HE 2, and is preheated by concentrated solution from the generator. In the generator, the dilute solution boils in a vacuum vessel and releases the same amount of water vapor as absorbed in the absorber. The water vapor then flows into condenser HE 3 where it condenses and transfers heat to the boiler feed water.

The return water in the district heating system will enter HE 1 first, where it is used to cool the concentrated solution from the generator. Then, the water goes into HE 3 where it receives heat from the condensing water vapor released from the dilute solution. Then, the return water goes into the boiler for the main heating.

In the absorber, the water vapor pressure difference between the flue gas and the solution surface drives the mass transfer for the water vapor latent heat recovery. Therefore, even though the solution temperature is not as low as the cold water temperature, the system still has good heat recovery.

3. Heat pump system models

The performance of the heat recovery systems was evaluated using models for the gas boiler, the OAHP system, and the EHP and AHP systems.

3.1. Combustion model for the natural gas boiler

For the combustion in the natural gas boiler, the natural gas reacts with the oxygen in the air and produces CO_2, N_2 and H_2O