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Thermodynamic performance analysis of a novel electricity-heating cogeneration system (EHCS) based on absorption heat pump applied in the coal-fired power plant

Hongsheng Zhang, Zhenlin Li, Hongbin Zhao *

College of Machinery and Transportation Engineering, China University of Petroleum, Beijing 102249, China
Beijing Key Laboratory of Process Fluid Filtration and Separation, China

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ABSTRACT

A novel electricity-heating cogeneration system (EHCS) which is equipped with an absorption heat pump (AHP) system to recover waste heat from exhaust steam of the steam turbines in coal-fired thermal power plants is proposed to reduce heating energy consumption and improve the utilization of the fossil fuels in existing CHP (Combined Heat and Power) systems. According to the first and second thermodynamic law, the changes of the performance evaluation indicators are analyzed, and exergy analyses for key components of the system are carried out as well as changes of exergy indexes focusing on 135 MW direct air cooling units before and after modification. Compared with the conventional heating system, the output power increases by about 3.58 MW, gross coal consumption rate and total exergy loss respectively reduces by 11.50 g/kW h and 4.649 MW, while the total thermal and exergy efficiency increases by 1.26% and 1.45% in the EHCS when the heating load is 99,918 kJ at 75% THA condition. Meanwhile, the decrement of total exergy loss and increment of total exergy efficiency increase with the increasing of the heating load. The scheme cannot only bring great economic benefits but also save fossil resources, which has a promising market application potential.

1. Introduction

With continuously increasing of energy source shortage and environmental pollution caused by the increase of fossil energy consumption, the renewable energy is expected to be alternatives to fossil energy [1]. As a result, renewable energy has been paid high attention and rapidly developed to solve the problems created by fossil fuels, including solar, biomass energy, wind, etc. [2,3]. However, some problems have not been solved and hinder the further application of the new energy source at present, such as technical problems and higher cost [4,5]. The share of the renewable energy in the energy consumption will be still significantly small [6]. Therefore, the most considerable energy source is those saved through energy saving transformation technologies to improve the energy conversion efficiency, which has been highly valued in recent years [7,8].

Simultaneously, a large number of waste heat that is not directly utilized in the conventional thermodynamic processes due to the lower temperature is dissipated in the word every year [9,10]. However, with the help of some technical means, this part of waste heat can be recycled, such as organic Rankine cycle, electrical turbo-compounding, supercritical Rankine cycles, heat pump system and so on [11–13]. In recent years, waste heat recovery has been paid more and more attention and studied in many researches. The waste heat recovery has become an important way to reduce fuel consumption, which cannot only improve energy efficiency but also reduce pollution to the environment [14,15].

Cogeneration that produces electricity and heat at the same time is an efficient energy utilization system to save energy source, which has been recognized and developed in the word [16–18]. Additionally, cogeneration cannot only make energy be used more fully, but also reduce pollution to the environment by reducing emissions, which is beneficial to the sustainable development of the society [19]. The thermal efficiency of the cogeneration central heating system can increase by 50% compared with the decentralized heating system. The cogeneration central heating will become the main heating manner in China due to higher energy utilization

* Corresponding author at: College of Machinery and Transportation Engineering, China University of Petroleum, Beijing 102249, China.
E-mail addresses: zhangguotang@aliyun.com (H. Zhang), zhenlinli@263.net (Z. Li), hbzhao@cup.edu.cn (H. Zhao).

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Nomenclature

Abbreviation

CHP	Combined Heat and Power
AHP	absorption heat pump
EHCS	electricity-heating cogeneration system
THA	turbine heat acceptance
COP	coefficient of performance
LP FWHs	low-pressure feedwater heaters
HP FWHs	high-pressure feedwater heaters
HPT	high pressure turbine
IPT	intermediate pressure turbine
LPT	low pressure turbine
ST	Steam turbine
HPH	high pressure heater
LPH	low pressure heater
DH	deaerator
RS	regenerative system
ACS	air cooling system

Variables

P	power (MW)
G	mass flow rate (kg/s)
h	steam specific enthalpy (kJ/kg)
q	heat released by per kg extracted steam (kJ/kg)
τ	enthalpy increment of per kg feed water (kJ/kg)
γ	heat released by per kg drain (kJ/kg)
$\bar{t}$	water specific enthalpy (kJ/kg)
a, b, c	mass concentration of lithium bromide
η	efficiency
Q	energy (kW)
α_h	the ratio of heat for heating to total heat in cogeneration
α_{h0}	the ratio of coal consumption for heating to total coal consumption in cogeneration
λ	heating correction factor
B	standard coal consumption (kg/s)
b_f	coal consumption rate (g/kW h)
$Q_{net,ar}$	net calorific value of standard coal (kJ/kg)
Ex	exergy (kW)
W	work (kJ)

Subscripts

j	extraction stage J of the turbine
ls	live steam
rhs	reheated steam
$crhs$	cold reheated steam
fw	feed water
cw	condenser water
z	total
bl	boiler
h	heating
b	generated power
p	the heating system with AHP
c	the conventional heating system
in	inlet
out	outlet
sh	shaft power
es	exhaust steam
ext	extraction
fwh	feed-water heater
dra	drainage
gen	generator
eva	evaporator
abs	absorber
con	condenser
dhs	driving heat source
r	refrigerant
ss	strong solution
ws	weak solution
hcw	heating condensate water
$lths$	low temperature heat source
sp	solution pump
$hhes$	heating heater extraction steam
bw	backwater
sw	supplied water
ex	exergy

efficiency [20]. With the 17% annual growth rate of the central heating areas, the heating load is also increasing rapidly, especially for large and medium-sized cities in northern China [21]. In response to this problem, the only way is to enlarge the existing heating capacity of the heating system. On the other hand, it is noteworthy that the waste heat from the exhausted steam of steam turbines includes more than half of the input energy of the whole power plant [22]. This part of the waste heat is usually emitted into the atmosphere through the condenser, which causes huge amounts of energy loss, low energy utilization efficiency, and pollution damage to the environment. There is a large potential to improve energy utilization efficiency to reduce energy resource consumption in the existing CHP systems [23]. Therefore, it is the best measure to utilize the recovered energy from the exhausted steam to enlarge heating capacity of the existing heating network and reduce pollutant emission. The absorption heat pump system is usually used to recover exhausted heat in the industry [24,25].

In order to explore the new waste heat recovery technologies by absorption heat pumps, a series of researches have been implemented in recent years. Garimella [26] simulated an absorption heat pump system with ammonia water as working medium that was applied to waste heat recovery of a gas stream to generate chilled and hot water. The simulation result shows that 2.26 MW of waste heat recovered can generate 1.28 MW of cooling capacity with the temperature 7 °C. At the same time, another stream was heated from 43 to 54 °C with the heating capacity of 3.57 MW. The saving of $1.2 million one year can be obtained. Sun et al. [27] presented a new waste heat recovery scheme from exhaust steam of steam turbines by the ejector heater and AHP in the CHP system. The research shows that the extracted steam flow rate can be reduced by 41.4%, and heating capacity can be increased by 66.7% when circulating water flow rate has no change. Additionally, the heating cost is lower than before. Bakhtiari [28] utilized AHP system to recover the exhausted heat from the bleaching effluent to produce hot water used by heat consumer in a Kraft pulping process, and evaluated the integrated system by a new methodology, namely, the simple payback time and net present value. The result shows the payback time is respectively 2.7 and 1.7 years corresponding to two cases when the steam price is 63 $/MW h. Ammar et al. [29] examined a scenario to utilize a large quantity of waste heat recovered by hybrid absorption heat pumps from a paper mill in a British coastal region to supply for the desalination process. The performance and economics are analyzed and make a comparison with the scheme that the waste heat is directly