Applied Thermal Engineering 136 (2018) 475–483

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Study of new cascade heating system with multi-heat sources based on exhausted steam waste heat utilization in power plant

Yan Li*, Weiqin Wang, YiFeng Ma, Wentao Li

College of Civil Engineering & Mechanics, Yanshan University, Qinhuangdao, PR China

HIGHLIGHTS

- Propose a new cascade heating system based on waste heat utilization.
- Present evaluation methods of large-unit safety and energy efficiency.
- Optimization study is performed from energy efficiency and economy.
- Energy consumption can be reduced by more than 33%.
- Total cost per heat output can be reduced by more than 22.3%.

ARTICLE INFO

Keywords:
Cogeneration
Turbine units
Waste heat utilization
Integration optimization

ABSTRACT

Utilizing waste heat of exhausted steam in power plant as a new type of heat source is a key direction to achieve both energy-saving and clean district heating. This paper firstly reviews current mature waste heat utilization technologies, including "absorption heat pump", "increasing back pressure of turbine" and "decreasing return water temperature of heat network". Using only one method is not applicable to recovery all the exhausted steam waste heat of multiple turbine units due to its respective limitations. In view of this technical difficulty, this paper proposes a new cascade heating system with multi-heat sources based on waste heat utilization. Extraction steam and exhausted steam are involved to achieve the cascade temperature-rise of heat network water. Corresponding evaluation methods are presented, including the last-stage safety of the large unit and the comprehensive energy efficiency of the new cogeneration heating system. Taking 2 × 300 MW water-cooled units as the example to actualize the new system, the effects of key parameters on energy efficiency and economy are analyzed, and then further researches about integration optimization of the new system are developed. In this study, first keep constant return water temperature of primary heat network, the optimal condition is gained. At this point, all the waste heat of exhausted steam is recovered, the energy consumption of power plant is reduced by 33% and the total cost per heat output c_t is reduced by 22.3%, compared with conventional cogeneration system. Then reduce the return water temperature in different level, both the energy consumption and the total cost per heat output c_t can be further lowered, the energy efficiency and the economy are better improved.

1. Introduction

Cogeneration is the most effective way to improve the energy efficiency of thermal power plant because of energy cascade utilization [1], and has been concerned by the countries all over the world [2]. In Denmark, cogeneration units accounts for more than 50% of thermal power generation [3,4], while Russia devotes to developing the gas-steam combined cycles, which supply more than 30% of thermal power generation [5,6]. Both have achieved significant energy-saving and environmental benefits. China attaches great importance to the development of coal-fired cogeneration [7,8]. In recent years, 300 MW turbine units have been fully put into service [9]. In these units, there is a large number of condensation heat of exhausted steam releasing by condenser, which is known as waste heat of exhausted steam, accounting for more than 30% of total energy consumption of unit [10]. If the waste heat is recovered to supply district heating, the heating capacity of plants can be increased to 25–40% and the energy efficiency of cogeneration heating system can be increased to 20–35%. Responding to the current energy policy in China, the coal consumption of average electricity supply of new-built and existing coal-fired thermal units

* Corresponding author.
E-mail address: leeyan2007@sohu.com (Y. Li).

https://doi.org/10.1016/j.applthermaleng.2018.01.033
Received 24 July 2017; Received in revised form 24 October 2017; Accepted 9 January 2018
Available online 08 February 2018
1359-4311/

Nomenclature

A_{ex}	the heat load proportion of the AHE substations
c_f	investment cost per heat output of the system (CNY/GJ)
c_o	energy cost per heat output of the system (CNY/GJ)
c_p	specific heat at constant pressure of water, kJ/(kg °C)
c_t	total cost per heat output of the system (CNY/GJ)
COP_h	coefficient of performance of AHP
D_c	mass flow of exhausted steam, t/h
$D_{c,v}$	volume flow of last stage, m^3/s
D_e	mass flow of extraction steam, t/h
f	electricity price, CNY/(kW h)
F_t	flow area of the last stage of large unit, m^2
G	flow of heat network water, t/h
G_1	flow of bypass water, t/h
h_c	specific enthalpy of exhausted steam, kJ/kg
h_e	specific enthalpy of extraction steam, kJ/kg
M_{ca}	Maher number of axial exhausted steam
N	hours of heating period, hour
P_b	backpressure of turbine unit, kPa
P_e	pressure of extraction steam, MPa
q_c	average heat power of exhausted steam, MW
q_e	average heat power of extraction steam, MW
Q_c	heat output of exhausted steam, MW
Q_e	heat output of extraction steam, MW
t_{H1}	outlet water temperature from condenser of unit 1#, °C
t_{H2}	outlet water temperature from condenser of unit 2#, °C
t_{H3}	outlet water temperature from AHP, °C
v_c	specific volume of exhausted steam, m^3/kg
$W_{eq,c}$	equivalent electricity of exhausted steam heating, kW h/GJ
$W_{eq,e}$	equivalent electricity of extraction steam heating, kW h/GJ
$W_{eq,s}$	equivalent electricity of system heating, kW h/GJ
x_{ec}	ratio of extraction steam heat to exhausted steam heat
Δd	terminal temperature difference of condenser, °C
τ_1	return water temperature of primary heat network, °C
τ_2	supply water temperature of primary heat network, °C

should be lowered to 300 gce/(kW h) and 310 gce/(kW h) respectively till 2020. The waste heat utilization is one of the key methods to achieve this goal.

In northern China, the energy consumption of building heating in winter is about 5.9×10^9 GJ per year, equal to 200 million tons of standard coal, in which the coal-fired boilers account for 2/3, so the air pollution is serious. The waste heat as a clean heat source to replace coal-fired boilers is non-polluting and low cost [11,12]. According to statistics, the account of waste heat produced from coal-fired power plants in northern China is about 14.4×10^9 GJ per year, if using 40% of it can meet more than 15 billion m^2 urban building heating theoretically.

Therefore, the waste heat utilization has become the focus of energy-saving of power plant and clean district heating of city in China.

2. Analysis of current technologies

The temperature of waste heat is low, especially for water-cooled unit, the back pressure is around 3–10 kPa, and the corresponding saturated temperature of exhausted steam is 25–45 °C, which is insufficient to heat the water of heat network. There are lots of ideas to recover waste heat [13], three of which have been matured and applied in practice:

(1) Set up absorption heat pump (AHP) in power plant: drive the AHP with the extraction steam of turbines to recycle the waste heat [14]. Some scholars have studied the match of the parameters between heat pump and steam turbine [15,16] and analyzed the system thermodynamic performance [17]. However, the design temperatures of primary heat network are usually 130/70 °C or 120/60 °C, restricted by the heating temperature ($t_H < 90$ °C) and the heating performance of AHP ($COP_h \approx 1.7$), the recovery rate of waste heat is only about 50% [13].

(2) Increasing back pressure of turbine: the temperature of exhausted steam is increased to heat the return water of heat network directly [18]. Some scholars have studied the heating process characteristics of direct air-cooled unit with high back pressure [19,20]. However, the last-stage blades of large wet-cooled units are longer, the operation safety of turbine is limited by minimum volume flow, so the increased amplitude of back pressure is limited. At present, the double-rotor interchange technology [21] is adopt: in heating period, original rotor is replaced by short rotor with less blades in low pressure cylinder to ensure the operation safety of turbine; while in non-heating period, original rotor is remained. However, due to the high temperature of return water, the back pressure of turbine needs to be increased sharply, which will inevitably reduce the electricity generation of power plants, the comprehensive energy efficiency is unsatisfactory. Besides, the thermal load and electric load inter-restrict with each other, which is inconvenient for unit adjustment.

(3) Decreasing return water temperature of heat network: set up absorption heat exchange (AHE) units at substations. Drive the AHE units with high-temperature supply water of primary heat network to decrease the return water temperature to about 20 °C or lower [22,23]. If all or larger proportions of substations install AHE, the temperature of return water back to plant will have a big decrease. It brings two advantages for district heating system: firstly, the temperature difference between the supply water and the return water is widened that can improve the pipe network transmission capacity; secondly, a more favorable condition for low-temperature waste heat recovery is created, especially when integrated with moderate increase of unit back pressure, the energy price of the heating system can be reduced significantly [24].

The installed form of units in most power plants are two or more sets, using only one method mentioned above is not applicable to recovery all the exhausted steam waste heat of multiple turbine units due to its respective limitations [13,25]. For example: only using "absorption heat pump" has a high investment and can't recover all the waste heat; only using "increasing back pressure of turbine" has a negative effect on electricity generation and is also bad for power dispatching and heat adjusting, it is difficult to be accepted if two or more units are arranged in this way. So since 2010, dozens of power plants in China have implemented waste heat utilization projects, which are based on above two single technologies [25], but with slim results.

Utilizing waste heat of exhausted steam to improve the performance of cogeneration system, the following principles should be achieved: ① theoretical waste heat recovery rate can get up to 100%, the heating capacity of power plant can be improved to the maximum extent; ② the negative effect on electricity generation can be reduced to the least, realizing a higher comprehensive energy efficiency of power plant; ③ minimize the total thermal price considering investment cost and energy cost, realizing a better economy of cogeneration.

In order to meet the three principles mentioned above, this paper proposes a new system integration idea, which can achieve simultaneous recovery and efficient utilization of waste heat of multiple units that single technology can't.