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Research Paper

Flue gas recovery system for natural gas combined heat and power plant with distributed peak-shaving heat pumps

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HIGHLIGHTS

- A flue gas recovery system with distributed peak-shaving heat pumps is proposed.
- The system can improve network transmission and distribution capacity.
- The system is advantageous in energy saving, emission reduction and economic benefits.

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ABSTRACT

District heating systems use distributed heat pump peak-shaving technology to adjust heat in secondary networks of substations. This technology simultaneously adjusts the heat of the secondary network and reduces the return-water temperature of the primary network by using the heat pump principle. When optimized, low temperature return-water is able to recycle more waste heat, thereby further improving the heating efficiency of the system. This paper introduces a flue gas recovery system for a natural gas combined heat and power plant with distributed peak-shaving heat pumps. A pilot system comprising a set of two 9F gas-steam combined cycle-back pressure heating units was used to analyse the system configuration and key parameters. The proposed system improved the network transmission and distribution capacity, increased heating capacity, and reduced heating energy consumption without compromising heating safety issues. As such, the proposed system is advantageous in terms of energy saving, emission reduction, and economic benefits.

1. Introduction

For large area district heating systems in China, the heating system comprises a primary and secondary network. The heat requirements are predominantly derived from two sources: cogeneration of heat and power [1] and large-scale coal-fired boilers [2]. The heating demands of urban heating system fluctuate with temperature changes. As such, basic heat source loads generally prioritize high efficiency, high initial investment and low running costs (such as the cogeneration heat sources), whereas, peak-shaving heat sources typically involve low investment, flexible adjustment and high running costs (such as the gas boiler heat source).

There are two kinds of peak-shaving methods: centralized and distributed. Centralized peak-shaving refers to the placement of the peak-shaving heat source at the main heat source plant. During cold periods, the basic load heat and peak-shaving heat are both sent into the primary network; heat then comes into the secondary network and finally reaches the consumer. Distributed peak-shaving refers to the implementation of gas boilers to directly supplement heat into the secondary network. During cold periods, only the basic load heat is sent into the primary network; the peak-shaving heat is separately sent into the secondary network. Wang [3] analyzed the location of peak heating in combined-heat-and-power-plant-based district heating systems. The results showed a collocation for superior peak-shaving distribution where heating energy efficiency was enhanced. Here, the primary network only undertook base load heat, thereby avoiding peak load heat transport regulations, improving the primary network utilization rate, achieving rapid adjustment and on-demand heating, and also improving general heating safety.

The literature addressing distributed peak-shaving technology generally refers to coal-fired boilers or combined heat and power plants (CHP) as the main heat sources and gas boilers as the peak-shaving source. Wang [4] studied a district heating system with a coal-fired CHP as the main heat source and a gas-fired boiler

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Nomenclature

α	peak-shaving ratio
B	fuel consumption in direct fired generator, kg/h
c_p	specific heat at constant pressure, kJ/(kg K)
ΔC	investment-increment, Yuan
ΔR	decrease of operation cost, Yuan
G	gas consumption, N m^3
H	calorific value, kJ/N m^3
m	mass flow rate, kg/h
η	efficiency
q	heat of direct fired generator, kJ/kg
Q	heat load, MW
Q'_{load}	design heat load of combined heating system, MW
t	temperature, °C
W	power generation amount, kW h
Y	investment-increment payback period, year

Subscripts

ab	absorber of absorption heat pump
AHP	absorption heat pump
b	base heat source
co	condenser of absorption heat pump
ev	evaporator of absorption heat pump
ex	heat exchanger
g	supply water
ge	generator of absorption heat pump
h	return water
hge	high-pressure generator of absorption heat pump
l	lower (calorific value)
in	inlet
out	outlet
p	power supply
ps	peak-shaving heat source
1	primary network
2	secondary network

as the peak-shaving source. This study analyzed different heating combination scenarios characterized by the basic heat load ratio (β) and an optimized β using a minimum net heating cost. Wang [5,6] studied combined district heating systems with gas-fired boilers for peak heating loads. This study analyzed the feasibility of increased energy savings and then developed an atmospheric environmental assessment model for the system. Other studies [7,8] used a regional (Tianjin, China) boiler room as the test subject, then conducted experiments on peak-shaving coefficients and pipeline safety. Another study [9] explored the safety and security aspects of gas boiler peak-shaving.

Unlike boiler peak-shaving, distributed heat pump peak-shaving uses a heat pump to adjust heat on the secondary network in substation. The technology enables the adjustment of heat in the secondary network while simultaneously reduces the return-water temperature of the primary network (using the heat pump principle). A combination of waste heat resources and low temperature return-water can recycle more waste heat at the peak-shaving condition, thereby further improving the system heating efficiency. It also improves network transmission and distribution capacity, thereby ensuring safety across the heat chain. In a CHP plant, low temperature return-water was used to recover the exhaust steam of a turbine; the relevant peak-shaving ratios and influencing factors were studied. At present, in Beijing City, a coal-fired CHP plant has been replaced by a cleaner natural gas CHP plant. Now, due to the growth of heating requirements, the problem of insufficient heat sources is becoming more prominent. Distributed heat pump peak-shaving can significantly increase the heat supplying capacity of an existing system. Here, the main heat source remains unchanged but a small amount of natural gas is consumed to expand the heating area while simultaneously recovering significant amounts of flue gas waste heat of the CHP plant.

This paper introduces the system processes and parameters of the proposed model and also provides an analysis of thermodynamics, energy efficiency and economic viability. The results show that a significant economic advantage can be achieved.

2. Flue gas recovery system for natural gas combined heat and power plant with distributed peak-shaving heat pumps

At present, the 9F level gas steam combined cycle unit is the preferred model for gas cogeneration district heating systems because its utilization of natural gas is highly efficient [10,11]. There are two main turbine models: extraction condensing and back pressure steam. The extraction condensing turbine system has a low heat-to-power ratio, which means that its heating capacity is insufficient for district heating. The back pressure steam turbine, which utilizes Synchro-Self-Shifting (SSS) clutch technology [12,13], increases the heat-to-power ratio; however, this increase is not cost effective.

This paper presents a system that uses two 9F class gas turbines (back pressure steam) as the main heat source and a distributed heat pump as the peak-shaving heat source (Fig. 1).

In substations, supply water of the primary network can be used as a driving force to realize heat exchange between the primary and secondary networks by using an absorption heat-exchanger technique. This principle is based on absorption cycles, using lithium bromide as the working fluid [14–16]. The coefficient of performance (COP) of the absorption heat pump was approximately 0.7. The return temperature of the primary network was decreased to approximately 20 °C, then supplemented by a gas driven peak-shaving heat pump to further reduce the return temperature to approximately 10 °C. Low temperature conditions are created in power plants in order to recover waste heat. The heat transport capacity of the primary network was increased, thereby significantly reducing the investment requirements. The temperature difference between supply/return water change from 60 to 100 °C, and the heat transport capacity of the primary network can be improved by approximately 60%.

A CHP plant uses a plate heat exchanger, a steam driven absorption heat pump and a direct contact heat exchange tower to recover waste heat [15,16]. The return water of the primary network was heated by a flue gas-water heat exchanger and an absorption heat pump, which heated the water to 120 °C via a steam-water heat exchanger. The flue gas from the waste heat boiler was approximately 90 °C. The dew point temperature of the flue gas is approximately 40 °C, and the recovery condensation heat of flue gas is difficult by the flue gas-water heat exchanger, so the flue gas was cooled to approximately 50–60 °C by the flue gas-water heat exchanger and was then used as a low-grade heat source for the absorption heat pump, which was cooled to approximately 20–30 °C. The turbine extraction steam was separately into the absorption heat pump and steam-water heat exchanger. During the process, water was heated by the following mechanisms: flue gas, absorption heat pump (absorption heat pump heat from