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Energy efficiency analysis of condensed waste heat recovery ways in cogeneration plant

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ABSTRACT

Making full use of condensed waste heat is an effective approach to increase heating capacity and reduce air pollutant emissions of the cogeneration plant. In this article, the heating equivalent electricity method is adopted to evaluate energy efficiencies and applicability of different condensed waste heat recovery ways, such as the condenser, the single-effect lithium bromide absorption heat pump and the bleeding-steam-driven compression heat pump. The following discussion is based on a 300 MW water-cooling steam turbine heating system and a 300 MW air-cooling steam turbine heating system. Combining with the characteristics of the water-cooling steam turbine and the air-cooling steam turbine, main factors affecting energy efficiencies are analyzed. Applicability evaluations of these condensed waste heat recovery ways are made by comparing energy efficiencies with each other under design conditions. Analysis shows that direct heat exchange by the condenser should be given the first priority. The condenser is most suitable to provide basic heating load. For the heat source composed of several steam turbines, the corresponding condensers should be connected in series. The proportion of steam turbines with high backpressures should be controlled due to high energy consumptions and inflexibility of adjustment. When supply water temperature is low, a surplus of bleeding steam pressure causes large irreversible loss in the generator of the single-effect absorption heat pump. A waste of energy grade of the bleeding steam makes the energy efficiency of the single-effect absorption heat pump lower than that of the bleeding-steam-driven compression heat pump. However, when bleeding steam pressure matches with the single-effect absorption heat pump, the energy efficiencies of them are basically the same. Therefore, the bleeding-steam-driven compression heat pump is more suitable when bleeding steam pressure is high. Due to large irreversible loss, energy efficiency of the heating network heater is the lowest.

1. Introduction

Cogeneration is the main heat source form of district heating in northern China. The condensed waste heat of the exhaust steam accounts for more than 40% of the heat supply from the cogeneration plant [1,2]. In order to increase the heating capacity of the heat source and to reduce its pollutant emissions, it is of great significance to make full use of the condensed waste heat from cogeneration plants [3–5].

Currently, direct heat exchange and different kinds of heat pumps are the most common methods to recover condensed waste heat. The two main technologies adopted for direct heat exchange are absorption heat exchange technology [1,6–9] and double backpressure dual rotor swap technology [10–12]. With absorption heat exchange technology, absorption heat exchangers in the substations are driven by hot water from the cogeneration plant. In this way, the return water temperature of primary heating network can be decreased to 20 °C. This reduction of the return water temperature creates favorable condition for complete recovery of the condensed waste heat. Moreover, it brings three obvious advantages. Firstly, the condensed waste heat with low energy grade replaces the heat supplied by the bleeding steam, which reduces energy consumptions of the heat source. Secondarily, heating capacity of the cogeneration plant can be greatly promoted by complete recovery of the condensed waste heat. Lastly, it increases transmission capacity by enlarging temperature difference and effectively saves electricity consumption of water pumps. The absorption heat exchange technology is most suitable for

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Nomenclature

COP	coefficient of performance
E	electricity output, kW h
H	enthalpy, kJ/kg
HE	heating equivalent electricity, kW h/GJ
IP	intermediate-pressure cylinder of the steam turbine
LP	low-pressure cylinder of the steam turbine
m	flow of the steam, t/h
P	pressure, kPa
Q	quantity of heat, MW or GJ
R	rate of condensed waste heat recovery
T	temperature, °C
V	valve
va	value

Greek symbols

Δ	temperature difference
δ	relative error rate
η	internal efficiency

Subscripts

af	after change
ag	generator of the single-effect lithium bromide absorption heat pump
ah	actual heating mode
b	backpressure
bf	before change
bs	bleeding steam
c	condensed water
cn	condenser
cp	bleeding-steam-driven compression heat pump
cr	pure condensing mode with reference backpressure
cw	compression work
d	design value
dr	drain water
es	exhaust steam
et	theoretical enthalpy of the extract steam
ex	extract steam
he	heat exchange
hh	heating network heater
hr	heating mode with reference backpressure
hs	heat supply of the heating system
ilp	inlet of the low-pressure cylinder
is	inlet of the stage
min	minimum value
ms	main steam
n	stage number of the steam turbine cylinder
os	outlet of the stage
res	recovered exhaust steam
s	supply water
sf	steam flow of the stage
si	simulated value
sp	single-effect lithium bromide absorption heat pump

saturated or long distance heating networks. However, the disadvantage of the technology is the large initial investment of the substations.

For the double backpressure dual rotor swap technology, supply water temperature of the condenser can be promoted by retrofitting both the internal structure of the low-pressure cylinder and the condenser. The advantage of this technology is that its initial investment can be much lower. However, three aspects also lead to disadvantages. First of all, operating with high backpressure has big negative effects on power generation, especially when the return water temperature of the primary heating network is high. Furthermore, the retrofitted units should afford basic heating load while the adjacent units take peak heating load, which makes heating load and power load cannot be adjusted independently. Additionally, not all of the steam turbines in the cogeneration plant can be retrofitted, which limits condensed waste heat recovery.

The single-effect absorption heat pumps [13–16] are widely used in cogeneration plant for condensed waste heat recovery. Generally, low evaporation temperature and high return water temperature of the primary heating network depress the performance of the single-effect absorption heat pump. Limited temperature rise makes it hard to fully recover condensed waste heat of the cogeneration plant.

The compression heat pump is categorized as electricity-driven compression heat pump [17,18] and bleeding-steam-driven compression heat pump [16]. The bleeding-steam-driven compression heat pump is generally used in the cogeneration plant due to a much higher thermodynamic degree of perfection than the electricity-driven compression heat pump.

Heating equivalent electricity method is adopted in this article to evaluate the applicability of these conventional ways of condensed waste heat recovery. Based on this method, main factors affecting energy efficiencies are analyzed and the energy efficiencies of these ways are compared with each other. This article is intended to provide helpful references for the design of the condensed waste heat recovery heating system and heat source configuration.

2. Calculation of heating equivalent electricity

The heat sources of cogeneration are bleeding steam and exhaust steam from the low-pressure cylinder of the steam turbine. High-temperature bleeding steam can be directly used to heat the circulation water of primary heating network or to drive heat pumps. Low-temperature exhaust steam can supply heat through direct heat exchange with the circulation water of primary heating network or may be used as a low temperature heat source for heat pumps.

Heating equivalent electricity intuitively reflects the reduction of electricity output resulted from heating by converting different grades of heat into the form of equivalent electricity. It is more suitable for energy efficiency evaluation of the cogeneration heating system. The lower the heating equivalent electricity is, the higher the energy efficiency is. Currently, the 300 MW steam turbine is most commonly used in cogeneration plant. This article provides an analysis based on a 300 MW water-cooling steam turbine of the model C350/294-24.2/0.43/566/566 and a 300 MW air-cooling steam turbine of the model CZK300/258-16.7/0.4/537/537. The main heating parameters are shown in Tables 1 and 2.

2.1. Heating equivalent electricity of bleeding steam

Bleeding steam is extracted from the pipe connecting the intermediate-pressure cylinder and the low-pressure cylinder of the steam turbine. In the initial period of heating, the flow of bleeding steam is low and the bleeding steam pressure is relatively high. The adjustment valve of low-pressure cylinder V_2 is fully opened. The flow of bleeding steam rises with gradual opening of the