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Research Paper

Heat transfer and thermal characteristics analysis of direct air-cooled combined heat and power plants under off-design conditions

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HIGHLIGHTS

- Heat transfer and heat supply characteristics of cold end are modeled.
- Coal consumptions in different modes, temperatures, fans columns are calculated.
- Optimal fans operation columns are proposed under different boundaries.
- Optimal fans mode reduces coal consumption up to 0.86 g/kW h.

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ABSTRACT

The distributed energy systems and efficient utilization of traditional fossil fuel are confronting great opportunities under present energy framework in which coal power dominating and renewable energy emerging gradually. Heating technology, especially cogeneration of heat and power (CHP), has been increasingly concerned and rapidly developed in recent years. It is an effective way for direct air-cooled power units to cope with rigorous complex environmental conditions, decrease coal rate and pollutant emission. This paper analysed the heat transfer characteristics of heating network and air-cooled island and obtained the cold end parameters of steam turbine under off-design condition, which is used to stimulate the operation state combined with relative parameters. The heat transfer characteristics of air-cooled island under different operation mode of air-cooled fans was acquired by introducing heat transfer coefficient; the power consumption of air-cooled island and the net power output were calculated with the relationship between frequency and power, air-cooled based on which the optimal operation and regulation method were determined. The optimized operation mode of both heating system and air-cooled system were determined under different ambient temperature and regulation method. The result showed that a maximum 0.86 g/kW h coal consumption reduction was reached in optimal fans operation mode, which meant the method scientifically supported the development of heating technology and further improved the processes of energy-saving and CO_2 reduction.

1. Introduction

Recently, fossil fuel shortages and the emission of greenhouse gases have produced a life-threatening challenge [1]. As a main fuel consumption sector, heating supply has large potential for energy conservation and emission reduction [2], especially through the introduction of combined heat and power (CHP), a reliable and environment-friendly technology with a history of over 100 years. Currently, heating supply technology has experienced three main generations (using steam, pressurised hot water over 100 °C, pressurised hot water under 100 °C as heat carrier, respectively), and the fourth generation technology, involving lower temperature level, will become mainstream technology in the near future [3], as studied by researchers [4].

CHP is an energy efficient and environmentally friendly way for energy conversion and utilization, especially when combines with the natural gas [5,6]. Researches are focusing on the old but vital technology from all over the world. To evaluate the energy conservation characteristics of CHP plants, a series of indicators have been proposed [7–11]. Meanwhile, to bring up the efficiency of CHP systems, a series of technical measures has been studied with respect to different system types and boundaries [12]. However, most of the recent published studies on CHP mainly focus on natural gas based small-scale tri-generation systems [5,6,13] and

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Nomenclature

D_c	exhaust steam flow	v_y	face velocity
Q_1	heat residents heating buildings transfer to environment	$\bar{\rho}_a$	average density of cold and hot air
Q_2	household radiator exhausted heat	c_a	specific heat capacity of air
Q_3	the heat heat supply condenser absorbs from exhaust steam	K_w	heat transfer coefficient of whole air-cooled island
q_v	volume thermal index of buildings	F_w	radiating area of radiator fin tube bundle
t_n	interior design temperature	α_i	condensation heat transfer coefficient of radiator in-tube c
t_w	environment temperature	δ_1	heat exchanger thickness
k_n	radiator heat transfer coefficient	λ	tube wall thermal conductivity
F_n	interior radiation area	α_0	out-tube forced convection heat transfer coefficient
c_p	isobaric heat capacity	Δt	temperature rise
t_g	supply water temperature	k_c	heat transfer coefficient of condenser
t_h	return water temperature	ξ_c	clean coefficient
t_s	steam temperature in air-cooled island entrance	β_t	correction coefficient of water temperature
h_c	enthalpy of condensed water	Φ_δ	correction coefficient of steam load change
A_w	windward area of air-cooled island		

units combining CHP with wind power or solar power [14,15]. Researches on solely conventional CHP with large-scale coal-fired units are relatively insufficient, which leads to the reality that operation and parameters of large-scale CHP systems have not been adjusted well with the increasing unit capacities, heat load scales and temperature levels. Besides, high CO_2 emission led to rising interest in renewable energy. However, it is impossible to converted to renewable energy from original energy framework instantly as a result of national primary energy reserves and infrastructures like China, South Africa, India, Poland, etc. The coal-fired power plants will be an important energy in foreseeable future. Therefore, intensive study of large-scale coal-fired CHP systems is still considerable corresponding to current serious energy shortage and environmental degradation.

It is significant to improve heat supply from air-cooled coal-fired power generation units. Liu [16] concluded the meteorological parameters and environment condition influences on performances of direct air cooled power generating unit, but without the research about heat supply condenser. For direct air-cooled heat supply unit, Guo [17] calculated the extraction flow, extraction pressure and the heat supply condenser's minimum mass flow under different ambient temperature, then concluded generation parameters and heating parameters corresponding to several thermoelectric ratios. Xiao [18] considered the influence of wind on air-cooling CHP system numerically and experimentally, then analysed the optimal operating schemes of air cooling condensers. Yang [19] carried the research on heating reaction degree and axial thrust characteristics of high back pressure turbine, and provided a reference for the safe operation of the unit. For the system mentioned below, Zhang Pan [20] analysed the economy by modelling the impacts caused by circulating water flow and other parameters such as the temperature. Li [21] studied the operating characteristics of three heating modes, including high back pressure heating, steam heating and heat pump heating under different environmental conditions.

The paper is organized as follows: In Section 2, the heat transfer characteristics of heat supply network (Section 2.1) and air-cooled island (Section 2.2) is introduced. Then, the characteristics of heat supply in off-design conditions are discussed (Section3 3), including the introduction of quality control and quantity control (Section 3.1), and the analysis of air-cooled island when only part of fans are working (Section 3.2). In Section 4, after introducing the heat transfer characteristics of cold-end (Section 4.1), the power consumption (Section 4.2) and power variation of unit (Section 4.3) in off-design conditions are performed. Afterwards, the optimum operation mode and energy saving effect are discussed (Section 4.4). Finally, the conclusions are drawn in Section 5.

2. Direct air-cooled high back pressure heat supply unit model

We employ a direct air-cooled high back pressure heating unit as a case study as shown in Fig. 1. The main steam expands through high pressure cylinder (HP), intermediate pressure cylinder (IP), and low pressure cylinder (LP) in sequence to drive generator (G) for producing electricity and part of the steam is extracted from HP, IP and LP to heat the feedwater in H1-H3, deaerator (DEA) and H4-H7. Part of the exhausted steam is condensed in air-cooled condenser (ACC), and the other part is condensed in heating condenser (HC) to heat water in heat supply network (HSN). During steam expansion, a secondary turbine (ST) is configured to drive FWP for less power consumed.

2.1. Heat transfer characteristics of heat supply network

Exhaust steam flow D_c of direct air-cooled unit which operating with high back pressure is divided into two parts. D_{c1} is the heat source for heat supply network, and D_{c2} is cooled by air-cooled island.

Ignoring heat and mass loss in the process of transportation, the heat that residents heating buildings transfer to environment (Q_1), household radiator exhausted heat (Q_2) and the heat that heat supply condenser absorbs from exhaust steam (Q_3) are equal:

$$Q_1 = Q_2 = Q_3 \tag{1}$$

The heat that heated buildings transfer to environment is:

$$Q_1 = q_v \cdot V \cdot (t_n - t_w) \tag{2}$$

where, q_v $(W/(m^3 \cdot K))$, $V(m^3)$, $t_r(^\circ C)$, $t_w(^\circ C)$ represent the volume thermal index of buildings, building volume, interior design temperature and environment temperature, respectively.

Heat that heaters dissipate to interior room is:

$$Q_2 = k_n \cdot F_n \cdot (t_p - t_n) \tag{3}$$

In this Eq. (3), $k_n(W/(m^2 \cdot K))$ is radiator's heat transfer coefficient; F_n is interior radiation area; $t_n(^\circ C)$ is hot water average temperature in heat exchanger.