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Identification of optimal operating strategy of direct air-cooling condenser for Rankine cycle based power plants

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HIGHLIGHTS

- Accurate off-design models developed for turbine subsystem and air-cooling condenser.
- Real operating data employed to characterize off-design performance of key components.
- Practical, quantitative operating guideline of air fans derived to maximize the plant profit.

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ABSTRACT

Direct air-cooling condenser has attracted significant attention in the last decade due to the employment of Rankine-cycle based power plants from renewable (e.g., concentrated solar) or traditional (e.g., coal) heat sources in water-scarce areas. The optimal operating strategy of direct air-cooling condenser to maximize net power gain under given plant status and boundary conditions is rather complicated due to strong impacts from the steam turbine subsystem and varying ambient conditions. This paper aims at determining, for various boundary conditions, the optimal operating fan frequency and the corresponding back pressure of a typical large-scale air-cooled coal-fired power plant via accurate off-design models of both the turbine subsystem and air-cooling condenser, which are derived by combining aggregated physical equations and real operating data. Several data pre-processing techniques, e.g., quasi steady-state selection, are employed first to improve the data quality. Then, the processed data are divided into two parts for the performance characterization of involved equipment and the accuracy testing of the derived models, respectively. The results show that good agreement has been achieved between the prediction of the established models and the real operating data within a wide range of load factor (50–100%), and ambient temperature (10–30 °C). To maximize the plant profit, practical and quantitative operating guidelines of the air fans have been derived, which are further employed to examine current operating strategy of the air-cooling condenser of the considered power plant. It is found that with a load factor over 85%, even the full-load operation of all equipped air fans cannot deliver the theoretical optimal back pressure for the steam turbine subsystem, indicating potential benefits of enlarging the condenser for high operating loads. The proposed identification procedure can be easily implemented as an online monitoring and supervision system to practically assist the optimal plant operation.

1. Introduction

Air-cooling condenser (ACC) can reduce water consumption at a cost of 5–10% penalty to the overall plant efficiency, due to the large amount of power consumed by air fans [1]. Air-cooling technologies have been widely applied to Rankine-cycle based power plants, e.g., coal-fired power plants and concentrated solar power plants (CSP) [2] located in the water-scarce areas. Particularly, in order to fast and significantly mitigate the environmental stress at the Eastern China, major Chinese power-generation groups started to systematically move many large-scale coal-fired power plants to the Northeastern China with rich coal reserve but poor water resources [3], where almost all power plants are coupled with air-cooling technology. For CSP, potential locations are all with high solar irradiation thus are mostly extreme dry areas so that ACC technology tends to be the best or even the only choice. Since CSP is potential to supply 25 % of the world's electricity by 2050 [4], ACC technology is expected to play more significant role in future.

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Nomenclature

Abbreviations

ACC	air-cooling condenser
CP	condensate pump
CSP	concentrated solar power
DA	de-aerator
FWP	feedwater pump
FWPH	feed-water preheater
G	generator
HPT	high pressure turbine
IPT	intermediate pressure turbine
LMTD	log mean temperature difference
LPT	low pressure turbine
MRE	mean relative error
RMSE	root mean square error

Symbols

A	heat transfer area, m^2
A_F	windward area of ACC, m^2
c_p	specific heat capacity, kJ/(kg·K)
D_w	thickness of the tube wall, m
$\dot{E}$	electric power, MW
f_{fan}	fan frequency, Hz
$f'_{saturation}$	relationship between the enthalpy and pressure of the saturated water
h	enthalpy, kJ/kg
K	heat transfer coefficient, W/(m^2·K)
l	number of the samples
$\dot{m}$	mass flowrate, kg/s
p	pressure, MPa
$\dot{Q}$	heat transferred, kW
Re	Reynolds number
t	temperature, °C
NTU	number of transfer units
V_F	face velocity, m/s
x_{mea}	measured value
x_{cal}	calculated value

Greek letters

η	efficiency
ξ	threshold in time-window method
ρ	density, kg/m^3
λ	thermal conductive of the tube, W/(m·K)
ε	effectiveness in ε–NTU method
ζ	surface fouling coefficient, m^2·K/W
ω	variables of the turbine subsystem
φ	variables of the ambient conditions

Subscripts

back	back pressure
c	condensate water
cond	condensing zone
drain	drain cooling zone
gain	net power gain
gross	gross power output
K	heat transfer
main	main steam
net	net power output
off	off-design condition
reheat	reheat steam
s	isentropic
tot	total
w	tube wall

Compared with traditional water-cooling technologies, ACC has many special issues to be addressed: (1) The performance of ACC is severely affected by ambient conditions, e.g., local temperature and wind speed. (2) Generally, the large amount of air needed due to low heat transfer coefficient of air increases the auxiliary-power consumption (thus, the operational costs) and reduces the net plant efficiency [5]. For given ambient conditions and plant load, increasing the operating frequency and number of air fans increases the fan power consumption but reduces the back pressure of steam turbine with an increase in the gross power generation. (3) The operating strategy of the fan matrix, usually divided into different clusters, can be complicated, since the performances of activated fan clusters are highly interacted due to the interactively-affected local ambient conditions. Considering all these aspects, for each given load and ambient condition, there should exist an optimal back pressure of steam turbine and corresponding operating number, configuration and frequency of the fan matrix to achieve the maximized plant profit. Unfortunately, the practical control of existing ACCs still depends highly on the operating experience and can hardly lead to the expected optimal conditions: The air fans are set at high speeds for high load factors or high ambient temperatures. No quantitative operating map of the fan matrix has been available for practical operation to better respond the varying boundary conditions.

Generally, four approaches can be employed to investigate the performance of the Rankine cycle and the ACC, which can reflect their practical performance with a reasonable accuracy so that quantitative operating maps of fan matrix can be derived. The first, commonly-used approach employs physical and empirical equations with critical reference/design values to investigate various issues related to the ACC operation, e.g., the effects of air-side flowrate and resistance on the efficiency [1], the anti-freezing exhausted steam [6], the optimal back pressure and fan-frequency regulation system for a fast load dispatch [7] and optimal ACC for a CSP plant [8]. The results obtained by this approach can only provide a general but not quantitative guidance for the ACC operation, since physical equations can hardly be accurate enough, due to various factors, e.g., unavoidable performance degradation [9,10] or equipment maintenance.

The second approach, employing numerical simulation, highlights and analyzes the distribution of the temperature and fluid fields in multiple scales (from fin, to fan, to fan clusters, to fan island, etc.) to provide useful information on how to improve the ACC design itself, e.g., the investigation of the effects of different wind conditions [11–13] and hybrid ventilation [14], heat transfer enhancement by improved design of heat exchangers [15–18], the performance study of a novel vertically arranged ACC [19]. However, this approach is rather computational expensive and time-consuming, thus is only applicable for ACC design but not for the identification of real-time operating strategy.

The third approach, experimental study, focuses on the performance characterization of a scaled, similar single tube, tube banks or tube systems [20], e.g., experimental investigation of different enhanced fin structures [21], the performance characterization of a novel air-cooling condenser [22]. Experiment investigation can usually offer much reliable performance data for real application; however, it is generally quite expensive, laborious, and can hardly be employed to guide plant operation.

The fourth approach, data mining with the aid of several optimization algorithms or criteria, e.g., artificial intelligence [23,24], evolutionary algorithms [25–29] and gray rational degrees [30], mainly