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Thermodynamic characteristics of thermal power plant with hybrid (dry/wet) cooling system

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ABSTRACT

A hybrid cooling system (HCS) consisting of dry and wet sections is proposed as a means to conserve energy and water by combining the benefits of both dry and wet cooling modes. A thermodynamic model of a 660 MW thermal power plant with HCS is established, and the variations in thermodynamic characteristics with respect to dry bulb temperature (T_A) and relative humidity (*RH*) are investigated using Ebsilon calculating code. Through comparison between the dry cooling system (DCS) and wet cooling system (WCS), HCS performance characteristics under different meteorological parameters are analyzed quantitatively. By comprehensively considering water and energy conservation indicators, the unique operation mode and ratio of the heat load shared by dry or wet sections are determined under various meteorological parameters. When T_A exceeds a certain value or *RH* falls below a certain value, the HCS does not operate in a hybrid cooling mode. Instead, its operation is equivalent to that of a WCS. We suggest that the cooling load of the wet section in the HCS be designed with the peak cooling load of the condenser under the most inhospitable meteorological parameters of the year. The findings reported here may provide guidance for HCS thermodynamic design and operation regulations.

1. Introduction

The wet cooling system (WCS) [1,2] is a common component in thermal power plants and other applications in metallurgical, chemical, refrigeration, and other industries. Evaporation and convective heat transfer occur simultaneously as warm water contacts ambient air directly on the packing in the enclosed box of the WCS. The WCS has better thermal performance and thermal stability than the dry cooling system (DCS), as its thermodynamics characteristics rely less on ambient winds. The WCS decreases the turbine back pressure and coal consumption in thermal power plants due to its high energy efficiency, but is unpopular in arid regions as it consumes a great deal of water [3]. Crosswinds severely impact WCS performance, as discussed by Ming Gao et al. [4,5]. Furthermore, visible plumes are easily generated when the saturated exhaust air from the WCS mixes with dry and cold ambient air, especially in winter [1,6–15]. These plumes induce several undesirable phenomena including fog, corrosion, moisture, and darkness in the surrounding area.

DCS are frequently utilized in thermal power plant located in arid regions to remedy the limitation of high water consumption of WCS. However, DCS is plagued by its following disadvantages. 1) The thermal performance is much worse than WCS. 2) The thermo-flow performance is severely deteriorated by unfavorable ambient wind [16–18], especially in the case that the wind blows from the main buildings of thermal power plant straightly [17]. 3) It has relatively unstable thermodynamic performance [19,20]. 4) Furthermore, because the specific heat of air is much smaller than that of water, let alone compared to the latent heat of water vaporization occurring in the WCS. The turbine back pressure and coal consumption per kilowatt hour is relatively high with DCS.

The hybrid cooling system (HCS) [1,11,21–24] containing dry and wet cooling sections exploits the advantages of both the WCS and DCS while mitigating their respective drawbacks; it has become a popular research topic in recent years accordingly. He et al. [23], for example, calculated the annual variations of thermal parameters including air mass flow rate, heat refection rate, and water saving capacity for a natural draft DCS, WCS, and HCS. They found that the HCS saves 70% water compared to the WCS as they released equivalent quantities of heat. Deziania et al. [25]

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Nomenclature

Abbreviations

B	boiler
C	condenser
CP	condensate pump
DCS	dry cooling system
FP	feed pump
G	generator
H	regenerator
HCS	hybrid cooling system
HD	deaerator
HPC	high pressure cylinder
IPC	intermediate pressure cylinder
LPC	low pressure cylinder
TD	feed pump turbine
WCS	wet cooling system

Symbols

AWR	mass flow rate ratio of air to water
c_p	specific heat under constant pressure (J kg^{-1} K^{-1})
H	height of packing in the wet cooling section (m)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
h_m	mass transfer coefficient (kg m^{-2})
i	enthalpy (kJ kg^{-1})
L	water consumption (t h^{-1})
M	mass flow rate (t h^{-1})
Me	Merkel number
N	fan shaft power (kW)
P	generating capacity (MW)
P_A	atmospheric pressure (kPa)
p	air pressure (Pa)
p_B	back pressure (kPa)
Q	heat transfer capacity (MW)
RH	relative humidity
t	temperature (°C)
T_A	ambient dry bulb temperature (°C)
T_{wb}	ambient wet bulb temperature (°C)
w	absolute humidity (g kg^{-1})

Greek symbols

α	percentage of heat load or air mass flow rate
β_x	mass transfer coefficient driven by humidity difference
γ	water vapor enthalpy at the bulk water temperature (kJ kg^{-1})
γ_0	vaporization latent heat as temperature equals 0 °C (kJ kg^{-1})
η	water saving rate
η_f	fan efficiency
Δ	rise (of pressure)

Subscripts

A	ambient air
a	air
ad	air in dry section
aw	air in wet section
d	dry air
off	off design
on	on design
Q	heat load
t	turbine steam
v	water vapor
w	water

experimentally measured the water consumption of a wet cooling tower with an air-to-air heat exchanger to find that it consumes 35% less water than a WCS. Asvapoositkul and Kuansathan [24] proposed that the thermal characteristics of the DCS, WCS, and HCS can be expressed as a function of their respective water-to-air ratios. They established computational models and investigated variations in HCS characteristics including fan power, input pump, rejected heat, and coefficient of performance (COP) with air mass flow rate or the portion shared by the wet section. Rezaei [26] developed a computer code to evaluate the thermal performance of wet and dry sections in the HCS for estimating water loss; they selected optimum operating conditions for the proposed HCS configuration accordingly. Dehaghani and Ahmadikia [27] studied the water and energy-saving effects after retrofit of a 12-cell wet cooling tower in the Isfahan thermal power plant using an HCS. They found that it consumes 9.4% less water on average after this retrofit and 64.6% less fan power via a high-precision airflow regulation method. Sarker et al. [28] experimentally tested the cooling capacity and pressure drop of bare-type copper tubes and fin tubes in staggered arrangement in a dry section to find considerable enhancement in the cooling capacity of fin tubes, but at the cost of an increase in energy consumption due to the increase in pressure drop.

In regards to energy efficiency, the primary design limitation of the HCS wet section is the WCS, which bears the full cooling load. The design limitation of the dry section is that the DCS bears the full cooling load and is water-consumptive. The variations of thermodynamic parameters and the principle of cooling load distribution in dry and wet sections under operating condition over different meteorological parameters are both basic science issues in HCS, which have apparently not been investigated. The research of these issues lays foundation for both design and operation regulation of HCS, in order to maximize the potential of energy and water saving of HCS. In this study, we investigated parameter-matching between HCS dry and wet sections to reveal the coupling operation mechanism between wet and dry cooling modes under a series of different meteorological parameters. We established thermodynamic models of the thermal power plant with an HCS, DCS, and WCS, and calculated the respective thermodynamic parameters over a range of ambient dry bulb temperatures (T_A) and relative humidity values in Ebsilon software. We investigated variations in HCS thermodynamic parameters with meteorological parameters under typical operation conditions and quantitatively analyzed the qualities of the HCS in regards to water and energy conservation as-compared to the WCS and DCS. We also determined the heat load and mass flow rate of air distributed in both dry and wet sections to provide some guidance for the design of each section in a typical HCS.

2. Mathematical modeling and simulation

A thermodynamic computational model of a thermal power plant with the above-mentioned hybrid cooling system is shown in Fig. 1. The thermodynamic cycle process consists of a steam power