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Optimal turbine pressure drop for solar chimney-aided dry cooling system in coal-fired power plants

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ABSTRACT

In solar chimney-aided dry cooling systems, the low-grade waste heat released by condensers in coal-fired power plants heats the inlet air of solar collectors, thus improves the power output and decreases the power consumption of fans. An analytical model of this hybrid system is proposed to study the characteristics of heat transfer and fluid flow in the water-air heat transfer, solar collector, heat storage layer, draft tower, and turbines. The fitting equation of the optimal turbine pressure drop for the hybrid system is derived, and the effects of the solar collector radius and solar radiation on power outputs are discussed. Results show that the optimal turbine pressure drop is positively correlated to the solar collector radius and solar radiation. However, a critical collector radius and a critical solar radiation for the turbine configuration exist. The performance of a hybrid system integrated with a 660 MW supercritical coal-fired power unit reveals that the optimization scheme proposed in this study outperforms the two schemes provided in the references.

1. Introduction

The Chinese power generation capacity has been increasing rapidly because of the fast growing economy. By the end of 2015, the Chinese power generation capacity was 1507 GW, while the coal-fired power generation capacity was over 990 GW, which accounted for 65.7% of the total [1]. However, coal-fired power generation leads to serious environmental issues [2]. China has been committed to reduce the coal consumption of coal-fired power plants (CFPP) in the recent years. One strategy is to employ high parameter instead of low parameter units [3], and the other is to develop renewable energy sources to reduce the use of coal [4]. Solar energy is one of the most promising alternative energy sources [5].

Solar chimney power plant (SCPP) is a low-temperature non-concentrating solar power generation facility. In SCPPs, solar radiation penetrates the solar collector roof and warms the ground (heat storage layer), which heats up the air above it. The suction force of the chimney located at the middle of the collector conducts the warm air flow along the leaned collector into the chimney, driving the turbines installed at the bottom of the chimney to generate electricity [6]. SCPPs have the advantages of simple construction, independence from water, and continuous operation [7]. Many studies have been conducted to exploit these advantages and characteristics of SCPPs by analytical and numerical methods.

Mullet derived the overall efficiency of SCPPs using a theoretical model and proved that the overall efficiency is mainly related to the height of the chimney and is approximately 1% for a height of 1000 m [8]. Ge and Ye reported an extremely low solar radiation intensity. They showed that the temperature difference between the air at the bottom of the chimney and the ambient air is usually less than or equal to 40 °C, which results in the low power generation efficiency of SCPPs [9]. The low power generation efficiency has become an obstacle to promoting the application of SCPPs.

Gannon and Backström showed that the power generation efficiency of SCPPs increased in direct proportion to the mass flow and the temperature rise of air in the solar collector [10]. Ming et al. indicated that geometric dimensions and turbine pressure drop have important effects on output power and system efficiency [11]. Guo et al. proposed a detailed analytical approach to evaluate the optimal turbine pressure drop ratio through an m-th power law assumption for SCPPs and investigated the influential factors of the value of m based on 3D numerical simulations [12]. Bernardes and von Backström [13] performed numerical simulations to evaluate the operational control strategies of SCPPs and indicated that the optimum turbine pressure drop ratio depends on the heat transfer coefficients in the collector. Guo et al. performed

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Nomenclature

A	area, m^2
B_0	heat consumption rate of the CFPP, kJ h^{-1}
b_0	coal consumption rate of the CFPP, kg h^{-1}
c	specific heat capacity, J kg^{-1} K^{-1}
D	diameter, m
f	friction factor
G	solar radiation intensity, W m^{-2}
k	heat transfer coefficient, W m^{-1} K^{-1}
K	pressure drop factor
h	Per unit mass enthalpy, kJ kg^{-1}
H	height, m
m	mass flow rate, kg s^{-1}
P	SCADCS power output, kW
P_c	additional coal-fired unit power output, kW
P_t	turbine power output, kW
P_r	Prandtl number
P_0	power output of the CFPP
p_{sf}	suction force generated by the draft tower, Pa
p	pressure loss, Pa
Q_{net}	lower heating value of standard coal, kJ kg^{-1}
q	heat transfer intensity, Wm^{-2}
R	radius, m
T	temperature, K
v	velocity, ms^{-1}

Abbreviations

CFPP	coal-fired power plants
DCCFPP	dry cooling coal-fired power plants
SCPP	solar chimney power plant
SCADCS	the solar chimney aided the dry cooling system

Greek symbols

α	absorption rate
γ	reflectivity
δ	thickness, m
ε	emissivity
η	efficiency
λ	thermal conductivity, W m^{-1} K^{-1}
ρ	density, kg m^{-3}
σ	Boltzmann constant
τ	transmissivity
Φ	heat exchange, W
ψ	Logarithmic correction factor
ν	kinematic viscosity, N s m^{-2}

Subscript

a	air
am	ambient air
cr	critical point
col	solar collector
con	condenser
csw	condensate water
dew	dew point
dt	draft tower
es	exhaust steam
ex	water-air heat exchanger
F	upwind of water-air heat exchanger
in	inlet
out	outlet
s	heat storage layer
t	turbine
w	cooling water

analytical and numerical analyses of the optimal turbine pressure drop ratio in SCPPs and found that the optimal ratio varies with the solar radiation intensity. In addition, the small difference between the optimal ratios obtained from the analytical and numerical models was verified [14].

Patel et al. used the ANSYS-CFX software to investigate the influence of geometry parameters, such as the collector inlet opening, collector outlet diameter, collector outlet height, chimney inlet opening, and chimney divergence angles of the SCPP, on a fixed solar chimney height and collector diameter [15]. Kasaeian et al. optimized the geometric parameters of a SCPP in Tehran [16]. Fasel et al. observed the time-dependent flow physics in the collector and chimney to provide a detailed insight into the fluid dynamics and heat transfer mechanisms using the ANSYS fluent [6]. To verify the accuracy of the theoretical models, Koonsrisuk and Chitsomboon compared five theoretical models through a computational fluid dynamics (CFD) simulation. They found that several theoretical models were consistent with the CFD results and thus recommended for the prediction of SCPPs' performance [17].

In northern China, dry cooling coal-fired power plants (DCCFPP) are widely adopted because of insufficient water. For CFPPs, the high back pressure of turbines leads to the release of more waste heat in the condenser during conventional thermodynamic processes [18]. To obtain a low turbine back pressure in DCCFPPs, numerous fans are employed to increase the cooling airflow and enforce cooling in the condenser, which increases the investment and auxiliary powers. Therefore, the design of turbine back pressure in DCCFPPs is determined based on the optimization of the thermal technique and economy. Furthermore, the increase in atmosphere temperature leads to an obvious increase in the back pressure of the turbine in DCCFPPs. According to the production field monitoring, the turbine back pressure in summer can exceed 30 kPa for a 660-MW supercritical DCCFPP, whereas it is only approximately 10 kPa for a wet cooling coal-fired power plant with the same capacity.

Hybridization seems to be an attractive mode for SCPPs to improve the energy conversion efficiency through the comprehensive and efficient utilization of energy. In recent years, several researchers have begun to hybridize SCPP with wind power generation, photovoltaic power generation, geothermal power generation, and CFPPs. Li et al. set a tornado-type wind tower at the outlet of the solar chimney, which increased the driving force of the chimney considerably through the high-elevation wind energy [19]. Marti-Herrero and Heras-Celemin replaced the surface of the solar chimney with PV modules, which were cooled by the air channel, and thus improved the efficiency of PV modules [20]. Shariatzadeh et al. integrated a solar chimney with solid oxide fuel and electrolysis cells to simultaneously generate heat and electricity [21]. Zou et al. integrated the SCPP with geothermal power plants to enhance the performance of natural draft dry cooling towers [22]. They proposed a structure optimization scheme for solar chimneys and collectors [23] and discussed the configuration of heat exchangers using the ANSYS FLUENT software [24].

In the CFPP, massive waste heat with low temperature is released in the condenser, which leads to a low power generation efficiency of less than 50%. Therefore, Zandian and Ashjaee proposed the hybrid combination of SCPP and CFPP. In this new system, the waste heat released by the exhaust steam in the CFPP was used to heat the inlet air in the SCPP to provide more suction capability for the chimney. They analyzed the influences of