International Journal of Heat and Mass Transfer 125 (2018) 1028–1042

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Numerical study on performance improvement of air-cooled condenser by water spray cooling

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ARTICLE INFO

Article history:
Received 14 January 2018
Received in revised form 7 April 2018
Accepted 1 May 2018

Keywords:
Water spray cooling
Air-cooled condenser
Back pressure of turbine
Water consumption

ABSTRACT

Water spray cooling is an efficient way to enhance heat transfer of the air-cooled condenser (ACC) of power generating unit under high ambient temperatures. Taking the air-cooled 300 MW power generating unit as object, the flow and temperature fields of ACC with water spray cooling were analyzed by numerical simulation with experimental validation. Based on the air flow field inside ACC cell, an improved water spray nozzles arrangement was proposed to enhance the cooling capacity. The inlet air temperature and back pressure of turbine were compared with that under the original nozzles arrangement. The water consumptions including that of water droplets pre-cooling evaporation in air flow, liquid film evaporation on the finned tube bundles, and drainage of redundant water were obtained. The influences of water spray rate, spray direction and nozzles distance on cooling performance were investigated. The results showed that the improved nozzles arrangement is expected to provide efficient cooling performance and significant reduction in back pressure of the objective power generating unit. The improved nozzles arrangement with upward spray direction and nozzles distance of 0.8 m can be applied to the design of water spray system in ACC. In addition, the obtained redundant drainage water under various ambient conditions provided the evidence for spray water rate optimization.

1. Introduction

Air-cooled condenser (ACC) cells applied in thermal power generating unit in arid regions have obvious water conservation benefit but with high efficiency penalty. The reason can be attributed to the cooling end performance decrease of the steam turbine compared with that of traditional wet cooling condenser. Moreover, the performance of ACC can be worse off at high ambient temperatures [1]. To enhance the cooling capacity of ACC, water spray cooling is a popular solution due to its simplicity, ease of operation and maintenance. Lots of direct air-cooled power plants have adopted the technology based on the tradeoff between additional water consumption and steam turbine efficiency, especially in summer hot days.

To optimize water spray design inside the "Λ" frame finned bundles of ACC cell, the spray cooling mechanism need to be well understood. The decrease of condensing temperature caused by spray cooling can be attributed to two reasons. Firstly, water droplets injected by nozzles mix with air and evaporate in the process of movement. It will reduce the dry-bulb temperature of cooling air and improve the humidity. Secondly, the residual droplets are attached to the finned tube bundles and form water film, which evaporates partially on the wet surface of the finned flat tubes. The excess water then is drained by streaming in liquid state. The latent heat transfer is the dominate part of heat transfer from water film to air which is caused by a small amount of water evaporation. Both mechanisms can enhance heat transfer and hence decrease the condensing temperature logically.

Over the past decades, droplets evaporation in air flow has been the subject of many studies both experimentally [2–7] and numerically [8–12]. The influences of different parameters were investigated, including that of air temperature, humidity, air velocity, and droplet size distribution. Tissot et al. [3,10] reported that small droplets injected in a counter flow situation yields the best cooling. Sureshkumar et al. [5] pointed out that for a specific water flow rate a smaller nozzle at higher pressure produced more cooling. In hot and dry conditions, cooling up to 14 C is attainable in both parallel and counter flow configurations. Montazeri et al. [9] proposed that the inlet dry-bulb air temperature has a strong effect on the amount of sensible cooling providing by a water spray system, and a lower amount of moisture in the air improves the performance of the spray system. Moreover, the cooling performance of the system is enhanced for wider drop-size distributions.

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.006

Nomenclature

A_d	surface area of droplet (m^2)
c_p	specific heat (J kg^{-1} K^{-1})
C	concentration of droplets (kg m^{-3})
C_D	drag coefficient
d_d	droplet diameter (m)
g	gravitational acceleration (m s^{-2})
h	heat transfer coefficient (W m^{-2} K)
h_n	polynomial coefficient for the convection heat transfer coefficient
k	thermal conductivity (W m^{-1} K^{-1})
L_h	latent heat of water vaporization (J kg^{-1})
m_d	mass of droplet (kg)
m_{d0}	initial mass of droplet (kg)
$\dot{m}_d$	mass flow rate of the droplets (kg/s)
$\dot{m}_{d0}$	initial mass flow rate of the droplet injection (kg/s)
Nu	Nusselt number
Pr	Prandtl number
q	heat flux (W m^{-2})
r_n	polynomial coefficient of non-dimensional loss coefficient
Re	Reynolds number
S_e	source term of energy (W m^{-3})
S_m	source term of mass (kg m^{-3} s^{-1})
S_{mo}	source term of momentum (kg m^{-2} s^{-2})
Sh	Sherwood number
t	time (s)
T	temperature (K)
u	velocity (m s^{-1})
V	volume (m^3)
$Y_{j'}$	mass fraction of species j'

Greek symbols

μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})

Subscripts

a	air
a1	inlet air
a2	outlet air
d	droplet
i, j, k	Cartesian coordinate directions
j'	species
s	surface
0	initial value

Alkhedhair et al. [2,11,12] found that spray dispersion is a major fact for the evaluation of a spray cooling system in natural draft dry cooling towers, and described clear trends of cooling enhancement with low air velocity or small droplet size distribution. Xiao et al. [7] suggested that the atomizing nozzles should be set in low air velocity region, which is benefit to the dispersion as well as evaporation time of droplets. The experimental results provide a design idea of nozzles arrangement in ACC cell that the nozzles may be better set in low air velocity region.

The non-fully evaporated droplets are attached to the finned tube bundles, forming the water film and evaporating on the surface of tubes and fins. A number of studies on evaporative cooled condensers used in refrigeration system have been made [13–16]. Hajidavalloo et al. [13] presented that application of evaporative cooled air condenser has significant effect on the performance improvement of the cycle, and rate of improvement is increased as ambient air temperature increases. Jahangeer et al. [15] found that the combined heat transfer coefficients obtained for the evaporatively-cooled condenser is very high for the different water film thicknesses on the condenser tube. In addition, numerous applications have been conducted for various heat exchangers [17–20]. Kim et al. [17] pointed out that under wet condition, both j and f factors of the flat tube heat exchanger are larger than those of the round tube heat exchanger. Li et al. [19] experimentally studied the falling film evaporation of water on 6-row horizontal enhanced tube bundles in a vacuum condition, and the correlations were derived to predict the heat transfer coefficients and the enhancement ratio. Zhang et al. [20] developed a model for evaporative cooling on flat-tube louver-fin heat exchangers, which can be used to predict heat exchanger performance under a variety of conditions with alternative water augmentation schemes.

However, the structures of evaporative cooled condensers or heat exchangers in aforementioned literature are remarkably different from air-cooled condenser in power generating unit. There were seldom researches on spray cooling regarding the wavy finned flat tube bundles, which are widely applied by air-cooled condenser in power plant. In our previous work [7], study on heat transfer enhancement of wavy finned flat tube bundle by water spray cooling was carried out by wind tunnel experiments. The correlations of water spray cooling heat transfer coefficients were fitted for tube bundles. In the present study, both processes, including that of droplet evaporation in air flow and film evaporation on the surface of finned tube bundle, are taken into account to investigate the optimization of water spray cooling at high ambient temperatures. The thermal-hydraulic performances of the whole condenser cell, as well as its influences on the turbine back pressure of power generating unit will be investigated, which can contribute to the optimal design of water spray cooling. An arrangement of spray nozzles inside ACC cells is proposed based on 2 × 300 MW direct air-cooled power generating units. Water consumption for various conditions is also analyzed. The results can be applied for the optimization of water spray rate providing the best compromise between back pressure drop and water consumption.

2. Physical model and numerical method

2.1. Physical model

Fig. 1 shows the physical model of the air-cooled condenser (ACC) cell with the finned tube bundles on both sides. The motor of bottom axial flow fan and the walkway are also considered inside ACC cell. As shown in Fig. 1, the overall size of the single ACC cell is $11.0 \times 14.0 \times 10.8$ m ($x \times y \times z$). The ambient air is draught by the axial flow fan with 9.14 m in diameter and flows through the finned tube bundles of "Λ" frame with top angle of 60°, taking away the condensing latent heat of the exhaust steam from turbine inside the flat tubes. In this study, the physical model of the axial flow fan with 6 blades is built according to its practical structure.

2.2. Mathematical model with numerical simulation

The Eulerian-Lagrangian approach is used to describe the thermal-hydraulic behavior of spray cooling inside ACC cell, by