Applied Energy 217 (2018) 496–508

Contents lists available at ScienceDirect

Applied Energy

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

A conceptual study on air jet-induced swirling plume for performance improvement of natural draft cooling towers

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HIGHLIGHTS

- The new concept of swirling plume significantly enhances cooling capacity of NDCTs.
- The cooling enhancement recovers power cycle output at high ambient temperature.
- The swirling plume creates an equivalent extra draft height above the tower.
- Air jet speed, direction, and nozzle size are the key controlling parameters.
- The concept consumes lower power than fan-forced coolers in long-term operations.

ARTICLE INFO

Keywords:
Natural draft cooling towers
Vortex cooling tower
Cooling enhancement
Swirling plume
Updraft vortex
Power cycle efficiency

ABSTRACT

In thermal power cycles including concentrating solar thermal (CST) plants, natural draft cooling towers (NDCTs) are widely used heat-dumping facilities. One inherent drawback of NDCTs is that their cooling performance can be compromised by changes in ambient conditions, particularly temperature, which inevitably reduces the net power output of the cycles. Current methods resolving this issue are limited in a few options including inlet air pre-cooling, exit air heating, and fan assistance, each with considerable operational or initial cost. To more economically reduce energy efficiency losses of the power cycles due to inefficient cooling, this paper proposes a new concept of swirling plume method for both dry- and wet-type NDCTs. The method is to rotate the plume strongly like a tornado in the tower upper part and above the towers to increase the overall tower updraft capacity (pressure). The swirling plume is induced by high-speed air jets distributed at certain locations using a much smaller flow rate. A numerical investigation on a 20 m-tall dry-type NDCT model has been conducted verifying that this concept increases the airflow and the water temperature drop of the heat exchanger by at least 53.6% and 3.57 °C (39.2%), respectively, under 35 °C ambient temperature. This cooling performance enhancement enables a half megawatt-scale sCO_2-based CST power cycle to recover its net power output, by 4.98%, to the level almost same as that at 30 °C ambient temperature. The air jet to create such a swirling plume consumes only 1/7 of the recovered power roughly. Compared with a traditional fan-forced cooler working under exactly the same condition, this concept requires significantly smaller energy in long-term operations as it would run only during temperature extremes. A simplified analytical modelling has found that the cooling tower performance is improved due to that the swirling plume creates an equivalent extra draft height on top of the tower which is attributed to two different vortical effects. The overall angular momentum of the swirl is a critical factor in these effects.

1. Introduction

Natural draft cooling towers (NDCTs) are widely used to remove heat in thermal power plants and many other industrial process. In Concentrated solar thermal (CST) power plants, the redundant heat downstream to turbines is usually removed by these facilities. The heat dump efficiency of the cooling towers is one of the crucial factors affecting the overall power conversion (heat-to-electricity) efficiency of the plants. Furthermore, the parasitic loss of power to run the cooling equipment is an important consideration. While NDCTs have the

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https://doi.org/10.1016/j.apenergy.2018.02.095
Received 12 December 2017; Received in revised form 9 February 2018; Accepted 12 February 2018

Nomenclature

A	area (m^2)
A_{Jn}	effective nozzle area normal to the jet stream, respectively (m^2)
a	jet direction angle (°)
b	jet direction angle (°)
C	inertial resistance factor in porous media
C_p	specific heat (J Kg^{-1} K^{-1})
C_μ	constant in turbulent viscosity
dn	thickness of porous media zone (m)
H	tower height (m)
h_r	convective heat transfer coefficient of radiator (heat exchangers) (W m^{-2} K^{-1})
K, K_e, K_t	laminar, effective, turbulent thermal conductivity, respectively (W m^{-1} K^{-1})
K_{to}	loss coefficient at the tower outlet
K_Σ	total pressure loss coefficient throughout the cooling tower
k	turbulent kinetic energy (m^2 s^{-2})
m_a	air mass flow rate (kg s^{-1})
m_{aJ}	jet air mass flow rate (kg s^{-1})
P	pressure (pa)
Pr, Pr_t	laminar, turbulent Prandtl number, respectively
ΔP_r	pressure difference across radiator (heat exchangers) (pa)
ΔP_{Ft}, ΔP_{Fs}	total pressure and static pressure of fan, respectively (pa)
q_r	heat flux of the radiator (heat exchangers) (W m^{-2})
R	cooling tower radius (m)
S	volumetric source term
T	temperature (K)
U	velocity component in x-, y-, or z- direction (m s^{-1})
V_F	volumic flow rate of fan (m^3 s^{-1})
v	velocity (m s^{-1})
v_a, v_F, v_J	air velocity inside the cooling tower, at fan outlet, and of the jet, respectively (m s^{-1})
v_{rJ}, $v_{\theta J}$, v_{zJ}	air jet velocity in radial, tangential and vertical (axial) directions (m s^{-1})
W_F, W_J	powers input of fans and jet nozzles, respectively (J s^{-1})
r, θ, z	cylindrical system co-ordinates: radial, tangential, and axial (vertical)
x	Cartesian system co-ordinates
z	elevation (m)
i, j, k	Cartesian co-ordinate serial

Greek letters

α	permeability in porous media (m^2) or velocity distribution factor
α^*, $\hat{\alpha}$	constants in pressure-strain tensor
β, β^*, $\hat{\beta}$	constants in pressure-strain tensor
γ^*, $\hat{\gamma}$	constants in pressure-strain tensor
ε	characteristic factor of plume vortex for static pressure
η_θ, η_z	factor of conservation of momentum
η_{Ft}	total efficiency of fan
ρ	density (kg m^{-3})
ρ_O, ρ_I	air density outside and inside the cooling tower, respectively (kg m^{-3})
μ, μ_e, μ_t	laminar, effective, turbulent viscosity, respectively (kg m^{-1} s^{-1})
σ_ω, $\sigma_{\omega 2}$	constants in the transport equation of ω
ω	turbulence energy specific dissipation rate (s^{-1})

Vectors

$\hat{\boldsymbol{e}}$	unit moment vector in co-ordinate directions
$\boldsymbol{M}$	momentum vector
$\boldsymbol{v}$	velocity vector

Tensors/matrix

D_{ij}, P_{ij}, S_{ij}	production tensors of Reynolds stresses
δ_{ij}	indentity matrix
ε_{ij}	dissipation tensor
Φ_{ij}	pressure-strain tensor

Subscripts

a	air or air side
E	energy
e	effective
F	fans
I, O	inside or inlet, outside or outlet
J	nozzle jet
M	momentum
r	radiator (heat exchangers)

unbeatable advantage of using no power, one of their drawbacks is that the cooling performance on these towers, especially natural draft dry cooling towers (NDDCTs), is highly compromised by changes in ambient temperatures: the higher the ambient temperatures, the lower the heat transfer rate to atmosphere. Because of this, NDCTs are always expected to be overdesigned to meet the desired cooling load at all time.

However, practical designs of NDCTs in thermal power plants are actually governed by a trade-off between the cooling performance and the capital costs. As the result, they only provide sufficient cooling loads for target ambient temperatures selected based on, for example, the 95th–98th percentile of hourly ambient temperature in a year, not 100%. During the small portion of a year when ambient temperature is higher than the design values, the cooling towers cannot cool down the cooling media sufficiently so that the overall power conversion efficiency drops. In base-load power plants, increasing fuel supply is a very common solution to offset the efficiency loss caused by poor cooling. A better option is to recover the cooling capacity during the periods at a less cost.

Currently, there are a few methods to improve the cooling performance of NDCTs against high ambient temperatures. For dry towers, various evaporation-based approaches have been proposed including dry-wet hybrid cooling [1–4] and inlet air precooling [5–7]. These methods consume large volumes of water, and require accessory water supply systems. They cannot be used in conjunction with wet cooling towers. One type of methods which is applicable to both dry and wet towers is devising a way to increase the temperature of hot air inside cooling towers to increase the air buoyancy so that the air flow rate. This includes heat injection [8] and solar radiation [9] downstream to the heat exchange zones (either heat exchangers or wet fills). Dynamical water distribution adjustment across the plane of heat exchangers to optimise the local heat transfer is also considered a useful method in enhancing both cooling tower types [10,11]. In the cases when crosswind presents, the cooling tower performance may be improved by taking use of the wind through windbreak walls, wind shells, deflectors, or the periphery of a tower base [12–23], which has been intensively studied in the past decade. More directly, air flow in NDCTs can be enhanced by deploying assistant fans at the inlets or above heat exchange zones [24,25]. The method usually chooses options from super-big fans [26], lots of smaller fans [27,28], and less small fans with