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Experimental study of the application of two trickle media for inlet air pre-cooling of natural draft dry cooling towers

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ABSTRACT

This paper is part two of a broader investigation into pre-cooling the air that enters natural draft dry cooling towers. Evaporative cooling of air is to some extent different from evaporative cooling of water. Two trickle media (Trickle125 and Trickle100) originally designed for evaporative cooling of water were studied in an open-circuit wind tunnel for evaporative cooling of air. Three medium thicknesses (200, 300 and 450 mm) and two water flow rates (10 and 5 l/min per m^2 horizontally exposed surface area) were used in the tests. The air velocities ranged from 0.5 to 3.0 m/s. The cooling efficiency and the pressure drop of the two media were curve fitted to yield a set of correlations. The pressure drop ranges for Trickle125 and Trickle100 were 0.7–50 Pa and 0.6–41.6 Pa, respectively. The cooling efficiencies of Trickle125 and Trickle100 fell within 15.7–55.1% and 11–44.4%, respectively. Generally, media with large effective surfaces provide high cooling efficiencies and high pressure drops; there is a trade-off between cooling efficiency and pressure drop when selecting a particular medium for a specific application. The water entrainment off the media was detected with water-sensitive papers, and both media had severe water entrainment at large air velocities.

1. Introduction

In part one, the authors experimentally investigated the possibility of evaporative pre-cooling of a natural draft dry cooling tower (NDDCT) using two film media (cellulose medium and PVC medium) [1]. This paper is part two of a broader investigation into pre-cooling the air that enters NDDCTs using two trickle media (Trickle125 and Trickle100).

With the increasing concerns regarding the problems associated with fossil fuels, renewable energy (e.g., geothermal and solar energy) has been taken into particular consideration [2]. Nowadays, geothermal and concentrated solar thermal power plants are on the summit of scientific research agendas. However, low-performance dry cooling may offer the only effective alternative since most geothermal and concentrated solar thermal power plants are located in arid or semi-arid areas [3,4]. To offset the low performance of dry cooling, especially during hot periods, several hybrid cooling approaches have been developed [5]. To improve the performance of NDDCTs during hot seasons, the present authors [6,7] introduced inlet air pre-cooling using wetted-medium evaporative cooling, which limits water consumption to the periods when the ambient temperatures are too high. The NDDCT is an alternative cooling method when large quantities of water are not available, such as in geothermal and concentrated solar thermal power plants. An NDDCT creates air flow through heat exchanger bundles with buoyancy due to the difference in air density inside and outside the tower [8]. Essentially, this density difference is due to the difference in air temperature. The performance of an NDDCT decreases when the ambient air temperatures are high. The reduced cooling tower performance decreases the efficiency of the thermal power stations the towers serve. For low-temperature binary-cycle geothermal power plants, the drop in power output can be even up to 50% from winter to summer [9]. The performance of an NDDCT is expected to be improved by reducing the temperature of the tower inlet air using wetted-medium evaporative pre-cooling.

Wetted-medium evaporative cooling is applied in many fields. There are two typical types: One type cools air, including evaporative coolers and cooling ventilation systems [10,11], greenhouse cooling [12,13], warehouse cooling and product storage [14], poultry, hog and livestock cooling, nursery cooling [6,7], inlet air pre-cooling of dry coolers [15], and inlet air cooling of gas turbines [16], which use a small amount of water to evaporatively cool the air. In this category, the latent heat of water evaporation is extracted from the air. It is usually assumed that this is a process where no heat exchange occurs with the external environment. The sensible heat in the air is converted to the latent heat of the water vapor that

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Nomenclature

A	area, m^2
a, b, c, d, m, n	constants
c_p	specific heat, J/(kg K)
G	mass velocity, kg/(m^2 s)
h_c	heat transfer coefficient, W/(m^2 K)
H	medium height, m
k	thermal conductivity, W/(m K)
K	loss coefficient
l	medium thickness, m
l_e	medium geometric length, $l_e = V/A_s = 1/\xi$, m
m	mass flow rate, kg/s
m_{ew}	water evaporation rate in kg/(m h K)
P	parasitic power loss, W
Δp	pressure drop, Pa
Q	water flow rate in l/min/m^2
Q_s	heat transfer rate, W
q	volumetric flow rate, m^3/s
RH	relative humidity, %
T	temperature, K
u	velocity, m/s
V	volume of medium, m^3
W	medium width, m
X	humidity ratio, kg_v/kg_a
NDDCT	natural draft dry cooling tower

Non-dimensional groups

Nu	Nusselt number, $Nu = (h_c\ l_e)/k$
Pr	Prandtl number, $Pr = \upsilon/\alpha = (\mu\ c_{pa})/k$
Re	Reynolds number, $Re = (u_a\ l_e)/\upsilon$

Greek symbols

α	thermal diffusivity, m^2/s
Δ	difference
η	cooling efficiency, %; efficiency
μ	dynamic viscosity, kg/(m s)
υ	kinetic viscosity, m^2/s
ξ	effective surface of medium, m^2/m^3
ρ	density, kg/m^3
β	integrated factor in Eq. (7)

Subscripts

1	inlet or before evaporative cooling
2	outlet or after evaporative cooling
a	air or air dry bulb
be	benefit
fr	front
s	sensible; transfer
v	water vapor
w	water
wb	wet bulb

joins the air stream, resulting in almost constant enthalpy and wet-bulb temperature of the air stream. Therefore, evaporative air cooling is also called adiabatic humidification or isenthalpic cooling of air. The other type cools water, such as wet cooling towers in thermal power plants [17], which have a large amount of hot water but evaporate only a small portion to cool the rest of the water stream. In this category, the water is generally cooled by water evaporation as well as sensible cooling due to the temperature difference between the water and the ambient air. The latent heat is the main source of evaporative water cooling. These two types of cooling use the large enthalpy of water vaporization, and their performance is limited to the wet-bulb temperature of ambient air. The above mentioned applications have been proven to be effective although the extra pressure drop introduced by the wetted media causes some parasitic losses. However, the extra pressure drop is very important for the inlet air pre-cooling of an NDDCT since the pressure drop reduces the air flow passing through the tower [6,7].

Wetted media (cooling pads in evaporative coolers, packages or fills as in wet cooling towers) are critical components in wetted-medium evaporative cooling systems [12,18]. Effective media should provide large contact surface areas for heat and mass exchange between the water and air flows and delay the fall of water to ensure that the exchange process lasts longer [12,19]. From the water formation point of view, the media fall into three main categories: splash, trickle (also known as hybrid media) and film [17]. Splash media break the water into a large number of droplets. Film media are designed to form water films. Trickle media, however, combine the production of small water droplets and surface-wetting water films [17,20]. Wetted media with different geometries and materials have been tested, and studies have been carried out to better understand their performance. Franco et al. [12] observed that choosing a suitable wetted medium requires knowledge of various parameters. Some researchers suggested that the factors influencing the medium selection are the cooling characteristic, pressure drop, cost and durability [21,22]. The selection of media is also determined by the type of process to be cooled, environmental conditions, water quality, space availability, location and economic requirements.

Generally, wetted media with high cooling efficiencies have high pressure drops as well. High cooling efficiency brings more cooling, but a high pressure drop produces more parasitic losses. There is a trade-off between the cooling efficiency and the pressure drop. For example, in pre-cooling NDDCTs, although pre-cooling decreases the inlet air temperature and thus improves the tower heat rejection, the extra pressure drop introduced by the medium reduces the air flow passing through the NDDCT, which in turn impairs the tower heat rejection [6,7]. The air flow rate in an NDDCT is constrained by the balance between the driving force (buoyancy, which is due to the air density difference resulting from the temperature difference between the air inside the tower and the outside air) and various flow resistances. The pressure drop of the medium contributes to the flow resistances, and therefore, a relatively low pressure drop is attractive for this pre-cooling application. This means, in this application, the pressure drop should be a major criterion during the selection of wetted media. After reviewing the literature, we found that, generally, trickle media offer larger surface areas than splash media and lower pressure drops than film media [20]. Trickle media are designed for wet cooling towers to evaporatively cool the process water, and their suitability for evaporative cooling of air is not known. In addition, previous work by the present authors experimentally investigated the possibility of evaporative pre-cooling of an NDDCT using two film media (cellulose medium and PVC medium). The present paper expands that study by experimentally investigating the possibility of two trickle media, both of which are made of propene polymer (PP). The current work can be distinguished from previous studies since it investigates the performance of two new types of wetted media for evaporative air cooling.

The objectives of the present work are as follows: (1) to experimentally obtain data on the cooling efficiency and pressure drop for the two trickle media when they are used in evaporative air cooling; (2) to develop correlations for the cooling efficiency and