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Study on the dynamic and thermal performances of a reversibly used cooling tower with upward spraying

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ABSTRACT

In subtropical areas, the RUCT (reversibly used cooling tower) can be used in a heat pump system. This study proposed an upward spraying RUCT, in which the aqueous solution is sprayed upward from the bottom, to reduce the drag resistance and enhance the efficiency of conventional RUCTs. A mathematical model considering rising and falling droplets simultaneously was developed based on conversation laws of mass, energy and momentum. The validity of the model was examined against the operating data measured in real conditions. Based on the validated model, the influences of different air velocities (2, 2.5, 3 m/s), droplet diameters (0.8, 1.0, 1.2 mm) and initial droplet velocities (6, 8, 10 m/s) on the displacement, velocity and temperature distributions of the sprayed droplet were discussed in detail. The results showed that, when the ratio of initial droplet velocity to air velocity closes to 1, smaller droplets will rise higher than the larger droplets, while for large ratio, the opposite is true. Droplet diameter had a large impact on the thermal performance and the droplet temperature rise in the descent stage was 1.5−2.4 times larger than that in the ascent stage. This study provides a theoretical foundation for optimization designing of the upward spraying RUCT.

1. Introduction

Cooling towers have been widely used in large refrigeration systems [1–6]. The aim of cooling towers is to release the heat from the condenser of the refrigeration system to the atmosphere via an evaporative cooling process of hot water. Cooling towers include two types, viz. direct and indirect cooling towers. Direct cooling towers spray hot water on packing which is used to spread out the water to film and thus increase its contact surface with air [7,8]. For indirect cooling towers, hot water goes through coils arranged in rows, while the air flows over the external side of the coil, and an additional circuit sprays water to cool the coils via evaporation [9,10]. The heat and mass transfer characteristics of cooling towers have been well understood and documented [8,10–13]. Corrosion and fouling problems are often encountered in cooling towers [14–16], airborne dusts and scale deposit on the coil or packing, resulting in a decrease of thermal performance for the cooling towers. Subsequent blockages in coils or packing could induce damage to the draught fan. In view of this, some scholars proposed a packing-free cooling tower [15–17], in which the packing is replaced by a set of efficient nozzles. In the packing-free cooling tower, the total contact area between water and air increases because the sprayed droplets become finer. A number of studies were reported to discuss the thermal performance of packing-free cooling towers, including water-jet cooling towers [17], shower cooling towers [15,16,18] and passive down-draft evaporative cooling towers [19]. All these studies focused on the cooling towers used for the refrigeration purpose. However, a cooling tower could also be served as an “evaporator” in a heat pump system to extract thermal energy from the ambient environment [20–23], this kind of cooling tower is usually called RUWCTs (reversibly used water cooling towers). In winter, a heat pump could accomplish the work of transferring heat energy from the outside environment to the indoor environment via using a relatively small amount of power [24–27], and provides a comfortable thermal environment for occupants.

The internal structure of RUWCTs is similar to the normally used direct cooling towers in which the packing is installed. However, the heat and mass transfer process in the RUWCTs is opposite to the conventional cooling towers. Instead of an evaporative cooling process between the hot water and ambient air, in RUWCTs, the water vapor contained in the air will condense at the cold liquid

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Nomenclature

A	activity coefficient
A_d	surface area of a droplet, m^2
A_d^*	surface area of droplets per unit time, m^2/s
C_p	specific heat, J/kg·K
C_d	drag coefficient
d	diameter, m
G	mass flow rate of dry air, kg/s
H	enthalpy of air, J/kg
h	heat transfer coefficient, $W/m^2 \cdot K$
g	acceleration of gravity, m/s^2
M	molecular weight, kg/mol
m_d	mass of droplet, kg
N_w	mass transfer flux of vapor, $mol/m^2 \cdot s$
Nu	Nusselt number
Pr	Prandtl number
P_v	vapor pressure, Pa
Q_s	solution flow rate, kg/s
r	correlation coefficient
R	resistance, N
R^2	absolute fraction of variance
Re	droplet Reynolds number
$RMSE$	root mean square error
Sc	Schmitt number
Sh	Sherwood number
T	temperature, °C
t	time, s
u	velocity, m/s
x	mole fraction of water
y	air humidity, kg/kg
Z	calculation height, m
Z_H	tower height, m

Greek symbols

μ_g	viscosity of air, $N \cdot s/m^2$
λ_0	heat of vaporization, J/kg
ρ_d	density of droplet, kg/m^3
ρ_g	density of gas, kg/m^3

Subscripts

0	initial state
d	droplet
f	falling
fb	force balance
i	inlet
g	gas
o	outlet
r	rising
s	solution
v	vapor
w	water

Superscripts

pure	pure water

film. Thermal energy is extracted from ambient air to water, and then transferred to the places needed to be heated. Previous studies on RUWCTs mainly focused on extracting thermal energy from the desuperheater and water was just used as the cycle fluid [20–23,28]. To apply the tower in subtropical areas, the RUCTs (reversibly used cooling towers) using anti-freezing solution were adopted. Using anti-freezing solution like calcium chloride solution as the working medium could decrease the freezing point of the medium and therefore makes it possible for RUCTs to extract heat from low temperature environment (in winter the dry-bulb temperature of ambient air in subtropics is 5 ~ 10 °C and the air is humid). Wu et al. [29,30] analyzed the performance characteristics of RUCTs using ANN (artificial neural network) and the simulation results agreed well with the experimental values with a satisfactory correlation coefficient in the range of 0.9249–0.9988. Wen et al. [31] studied the effect of air and fluid inlet temperature, air flow rate and liquid flow rate on the heat transfer coefficient of RUCTs. Studies in Refs. [29,31] focused on RUCTs operating under cross flow conditions and calcium chloride solution was adopted in their study. Cheng et al. [32,33] studied the closed RUCTs with anti-freezing solution flowing in the finned tubes. By using additional spray of anti-freezing solution on the finned tubes, the thermal efficiency of the tower was increased by 5–10%.

Since 2012, RUCTs have been put into use in subtropical areas in China. According to the users' feedback, problems of salt deposition and blockage in RUCTs were even serious, because the anti-freezing solution has more serious impact on packing or finned tubes than water. To solve this problem, an upward spraying RUCT is proposed in this study. As shown in Fig. 1(a), a set of efficient nozzles is installed at the bottom of the tower and there is no packing inside. The cold solution is sprayed upward from the bottom of the device. After the sprayed droplets reaching the vertexes, droplets begin to fall due to the impact of gravity. Air flows from the bottom of the device, exchanging heat and mass with the rising and falling droplets simultaneously. During the transfer process, condensation occurs at the surface of the droplets since the water vapor pressure near the surface of the droplets is lower than that of air stream. As a result, the aqueous solution absorbs the sensible and latent heat from the air, and then the solution is pumped to the evaporator.

The upward spraying RUCT has several advantages. First, as packing is removed, the equipment investment and drag resistance are reduced. Second, the fine droplets produced by the efficient nozzles have to go through an ascent stage and a descent stage, making the heat and mass transfer more sufficient. Third, in subtropical areas, conventional air source heat pumps need to defrost frequently due to the relatively high humidity in winter [27]. Unlike conventional air source heat pumps, heat pumps associated with RUCTs do not need to defrost, instead, they absorb the latent heat from the air, thus a considerable amount of energy is saved and more energy is extracted from the air. Fourth, in winter, an upward spraying RUCT could act as a wet scrubber to mitigate particulate pollution which has been becoming a very serious environmental problem in China in recent years [34–36]. As the solution temperature is lower than the wet-bulb temperature of the air, the mechanisms of thermophoresis and diffusiophoresis (caused by the temperature gradient and water vapor pressure gradient, respectively) play important roles in eliminating particulate pollution [37,38], and the particle removal efficiency is strongly influenced by the droplet dynamics and thermal performances of the upward spraying RUCT. However, up to now, the thermodynamic mathematical model on the upward spraying RUCT was rarely studied.

In this paper, a mathematical model concerning rising and falling droplets simultaneously was developed for the upward spraying RUCT. Air humidity, air temperature, droplet velocity and droplet temperature were calculated along the tower height using the Runge–Kutta method [39] which was adopted to solve ordinary