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Investigation on the thermal performance of a novel spray tower with upward spraying and downward gas flow

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HIGHLIGHTS

- A spray tower with upward spraying and downward gas flow (ST-UD) is proposed.
- ST-UD has no restriction on the minimum droplet diameter and no drift eliminator.
- A mathematical model was developed for the quick performance evaluation of ST-UD.
- ST-UD has high heat and mass transfer performance and particle scavenging performance.
- The impacts of operating parameters on thermal performance of ST-UD was evaluated.

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ABSTRACT

This paper presents the design and evaluation of a novel spray tower which called the reversibly used cooling tower with upward spraying and downward gas flow (RUCT-UD). Unlike conventional spray towers, RUCT-UD has no high-resistance drift eliminator and no restriction on the minimum droplet diameter, which gives it the potential to achieve better performance of heat and mass transfer and particle scavenging. A mathematical model was developed and validated by field experiments. This model is highly efficient in calculation due to the simultaneous consideration of rising and falling droplets. Using the model, the heat and mass transfer characteristics were investigated by a parametric study, which provides a theoretical basis for the tower design. After that, the performance of RUCT-UD was compared with that of other spray-type RUCTs. Results show that RUCT-UD is 45% shorter than RUCT-UU (the reversibly used cooling tower with upward spraying and upward gas flow) and RUCT-DU (the reversibly used cooling tower with downward spraying and upward gas flow), meanwhile it could realize a high thermal performance like RUCT-UU. The particle collection efficiency of $PM_{2.5}$ for RUCT-UD is 75.9%, which is higher than that of RUCT-UU (48.9%) and that of RUCT-DU (61.1%). The configuration of the proposed RUCT-UD might be applied to other spray towers for the performance improvement.

1. Introduction

Spray towers are used in many industrial applications, such as spray cooling [1,2], spray drying [3], humidification [4], dehumidification [5], CO_2 capture [6], desulphurization [7], desalination [8] and particulate removal [9]. Based on the gas flow direction, existing spray towers with vertical injection can be divided into four types: (1) Spray towers with downward spraying and downward gas flow (denoted as ST-DD), i.e., the co-current spray towers. (2) Crosscurrent spray towers, in which droplets are sprayed perpendicular to the moving gas flow; (3) Spray towers with downward spraying and upward gas flow (ST-DU), i.e., the countercurrent spray towers. (4) Spray towers with upward spraying and upward gas flow (ST-UU), as shown in Fig. 1.

Kang and Strand [1,2] indicated that gas velocity is the key factor affecting the performance of ST-DD. Zunaid et al. [10] concluded that the largest portion of the total exergy destroyed at the top of ST-DD. Muangnoi et al. [11] indicated that the second law efficiency of ST-DD is sensitive to reasonable variation in droplet diameter, liquid-gas ratio and tower height. Niksiar and Rahimi [12] developed a descriptive model for energy and exergy analysis of ST-DD. Their results showed that ST-DD has relatively low exergy efficiency. De Paepe et al. [13] identified droplet diameter as the most crucial parameter in the evaporation process for a crosscurrent spray tower. Sun et al. [14] determined correlations of droplet evaporation model for a crosscurrent

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Nomenclature

A	correction factor
A_d	surface area of a droplet, m^2
A_d^*	surface area of droplets per unit time, m^2/s
A_{sa}	sectional area, m^2
B	atmospheric pressure, Pa
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 gas, J/kg
h	heat transfer coefficient, W/(m^2·K)
h_m	mass transfer coefficient, kg/(m^2·s)
g	acceleration of gravity, m/s^2
M	molecular weight, kg/mol
m_d	mass of droplet, kg
N	particle number concentration, n/m^3
N_w	mass transfer flux of vapor, mol/(m^2·s)
Nu	Nusselt number
Pr	Prandtl number
P_v	vapor pressure of solution, Pa
P_v^{pure}	vapor pressure of pure water, 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	humidity, kg/kg
Z	calculation height, m
Z_H	overall calculation height, m

Greek symbols

μ_g	viscosity of gas, N·s/m^2
λ_0	latent heat of vaporization, J/kg
ρ_d	density of droplet, kg/m^3
ρ_g	density of gas, kg/m^3
η_{oe}	overall collection efficiency
η_{se}	single droplet collection efficiency

Subscripts

0	initial state
d	droplet
ds	droplet surface
f	falling
i	inlet
g	gas
no	nozzle outlet
o	outlet
oe	overall collection efficiency
r	rising
s	solution
se	single droplet collection efficiency
v	vapor
w	water

spray system. Yang et al. [15] proposed an optimized design method to improve the performance of a crosscurrent spray system.

Ali et al. [16] developed a one-dimensional plug-flow model to achieve the quick performance assessment of ST-DU. Wu et al. [17] showed that the solution concentration plays a major impact on the performance of ST-DU. Qi et al. [18] deployed a projection pursuit regression model to predict the performance of ST-DU. Cui et al. [19] conducted multivariate analysis to optimize the thermal performance of ST-DU. Mohan and et al. [20] conducted experimental investigations to quantify the performance of ST-DU for particle scavenging. The heat and mass transfer characteristics of ST-UU were investigated by a few recent studies [21–23]. Results indicated that the thermal performance of ST-UU is better than that of ST-DU due to the prolonged droplet detention time.

ST-DU and ST-UU have two drawbacks: (1) Restriction on the minimum droplet diameter or the maximum gas velocity. Choosing a smaller average droplet diameter for the spray system could enhance thermal efficiency and particle scavenging efficiency [24]. However, to prevent droplets being blown away by the upward gas flow, the droplet diameter needs to be larger than a certain value [19]. (2) High flow resistance. The high-resistance drift eliminators installed in ST-DU and ST-UU increase the fan power consumption. When gas velocity equals 3 m/s, a drift eliminator could cause more than 100 Pa pressure drop [25]. By contrast, the total resistance caused by tube banks and spray is less than 20 Pa [26].

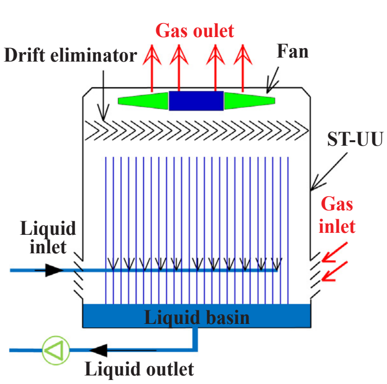

Fig. 1. Spray tower with upward spraying and upward gas flow.

To solve the drawbacks mentioned above, this study proposes a novel spray tower, namely the spray tower with upward spraying and downward gas flow (ST-UD). ST-UD has a special configuration, as shown in Fig. 2. The drift eliminator is removed. Gas flows from top to bottom and nozzles are installed at the bottom of the tower. The sprayed droplets rise first and then fall to the liquid basin under the influence of gravity and drag force. At the lower part of ST-UD, gas velocity direction changes and the droplets entrained are separated from gas stream by gravitational and inertial forces. To inhibit splashing droplets, a honeycomb structure mat is covered on the solution basin. The anti-splash mat also works as a filter to prevent dust from entering the evaporator and reduces the noise caused by the falling droplets.

ST-UD has lower flow resistance in comparison with ST-DU and ST-UU because it removes the high-resistance drift eliminator. ST-UD is shorter than ST-DU and ST-UU due to the influence of downward moving gas flow on the droplet displacement. The droplet detention time in ST-UD is longer than that in ST-DU and ST-DD. Most important of all, ST-UD has no restriction on the minimum droplet diameter, which gives it a potential to achieve better performance of heat and mass transfer and particle scavenging. ST-UD has the above-mentioned