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# Optimization of reversibly used cooling tower with downward spraying

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ABSTRACT

Heat pumps associated with reversibly used cooling towers present great potential for energy saving in subtropical areas. To study the heat and mass transfer characteristics of reversibly used cooling towers with downward spraying (DSRUCT) and optimize its thermal performance, a mathematical model was developed and validated through field experiments. Then a parametric study was conducted to study the impacts of initial solution temperature (−4 to −1 °C), gas velocity (2.5–4 m/s), initial droplet velocity (4–10 m/s) and droplet diameter (0.65–1.2 mm) on the heat rate, tower effectiveness and solution temperature distribution. According to the results of the parametric study, we proposed an optimization method established on the concepts of critical gas velocity and critical height. This method was based on multivariable analysis. Two operating parameters (gas velocity and droplet diameter) and one structural parameter (tower height) were simultaneously concerned. The results of this work provided a theoretical foundation for optimizing the thermal performance and saving initial investment of DSRUCT and other counter-current spray systems, e.g., dehumidification, desulfurization, spray cooling, and carbon capture.

## 1. Introduction

Heat pumps associated with reversibly used cooling towers (RUCT) present great potential for energy saving in subtropical areas [1–3]. RUCT is a device that absorbs thermal energy from ambient air in winter by direct contact between air and working fluid (water or anti-freezing solution). The thermal energy absorbed by the working fluid will be sent to the evaporator of the heat pump. Then the heat pump transfers the thermal energy to the indoor environment.

Reversibly used cooling towers include two types, viz. packed-bed RUCT and spraying RUCT. The packed-bed RUCT sprays working fluid onto the packing which is used to spread out the fluid to film and thus increase its contact surface with air. The performance characteristics of packed-bed RUCT were studied by Wu et al. [4,5], Tan et al. [6,7] and Wen et al. [8]. The packing in the packed-bed RUCT suffers from fouling problem after a certain time of operation. The spraying RUCT was proposed in 2016 by Cui et al. [9]. It replaces the packing with a set of efficient nozzles and therefore solves the fouling problem. However, the thermal efficiency of spraying RUCT (50–55.5%) is lower than that of packed-bed RUCT (around 75%) [9]. The decline of thermal efficiency was caused by the removal of packing and the heat and mass transfer characteristics of spraying RUCT. To optimize the thermal performance of spraying RUCT, it is important to comprehensively understand its heat and mass transfer characteristics.

Literature [9] illustrated the heat and mass transfer characteristics of an upward spraying RUCT by investigating the impacts of gas velocity, droplet velocity, droplet diameter on the solution temperature distribution and the droplet velocity distribution. The heat and mass transfer characteristics of similar packing-free spray systems such as packing-free cooling towers [10–15] and liquid desiccant dehumidification systems [16,17] were investigated through sensitivity analysis: the impacts of operating parameters and structural parameters (liquid to gas flow rate ratio, tower height, droplet diameter, droplet velocity, fluid temperature and gas velocity) on the thermal performance were studied. However, the above-mentioned studies were based on univariate analysis (with one varying operating parameter while other parameters were fixed at constant values). Since the effects of many operating parameters on the system performance could be non-linear, their

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Nomenclature

| | | | |
|---|---|---|---|
| $A$ | coefficient of correction | $SSE$ | sum of squared error |
| $A_d$ | surface area of a single droplet, m$^2$ | $t$ | time, s |
| $A_d^*$ | surface area of droplets per unit time, m$^2$/s | $u$ | velocity, m/s |
| $B$ | atmospheric pressure, Pa | $x$ | mole fraction of water |
| $C_d$ | drag coefficient | $y$ | humidity, kg/kg |
| $C_p$ | specific heat, J/kg·K | $Z$ | calculation height, m |
| $d$ | droplet diameter, m | $Z_{crit}$ | critical tower height, m |
| $D$ | mass diffusivity, m$^2$/s | $T$ | temperature, °C |
| $E$ | tower effectiveness | $Z_H$ | tower height, m |
| $G_y$ | mass flow rate of dry gas, kg/s | *Greek symbols* | |
| $H$ | enthalpy of gas, J/kg | $\mu_g$ | viscosity of gas, N·s/m$^2$ |
| $h$ | heat transfer coefficient, W/m$^2$·K | $\lambda_0$ | heat of vaporization, J/kg |
| $h_{\mathrm{m}}$ | mass transfer coefficient, m/s | $\rho_d$ | density of droplet, kg/m$^3$ |
| $g$ | acceleration of gravity, m/s$^2$ | $\rho_g$ | density of gas, kg/m$^3$ |
| $k$ | thermal conductivity, W/(m·k) | $\eta$ | thermal efficiency |
| $M$ | molecular weight, kg/mol | $\sigma$ | surface tension, N/m |
| $m_d$ | mass of droplet, kg | *Subscripts* | |
| $N_w$ | mass transfer flux of water vapor, mol/m$^2$·s | 0 | initial state |
| $Nu$ | Nusselt number | 1 | final state |
| $Pr$ | Prandtl number | $crit$ | critical condition |
| $p_v$ | vapor pressure, Pa | $d$ | droplet |
| $Q$ | Heat rate, kW | $ds$ | droplet surface |
| $Q_s$ | mass flow rate of solution, kg/s | $g$ | gas |
| $r$ | correlation coefficient | $s$ | solution |
| $Re$ | droplet Reynolds number | $v$ | vapor |
| $R^2$ | absolute fraction of variance | $w$ | water |
| $RMSE$ | root mean square error | $wb$ | wet-bulb |
| $Sc$ | Schmidt number | *Superscripts* | |
| $Sh$ | Sherwood number | 0 | pure water |

influences may change significantly when two or more operating parameters vary simultaneously. Therefore, multivariable analysis might be more appropriate for investigating the heat and mass transfer characteristics of spraying RUCT.

Many investigators had carried out work on the optimization of packed-bed cooling towers using different optimization techniques such as the entransy theory [18–20], the artificial bee colony algorithm [21], the effectiveness-NTU method [22] and the improved constrained parameter retrieval technique [23]. However, studies on optimization of spraying RUCT and similar systems were rarely reported. The thermal performance of spraying RUCT is quite sensitive to the droplet diameter, initial droplet velocity and gas velocity [9]. Also, in spraying RUCT, droplets will break up if the chosen droplet diameter is too large, and droplets will be blown away by the wind if air velocity is too large [24]. These restrictions lead to the fact that the optimization of spraying RUCT is different from that of packed-bed systems. Therefore, the main objective of this work is to develop an optimization method that is appropriate for the reversibly used cooling tower with downward spraying (DSRUCT) and similar packing-free systems. The heat and mass transfer characteristics of the DSRUCT were also comprehensively investigated by using both univariate analysis and multivariable analysis.

In this work, a mathematical model for DSRUCT was first developed and validated through field experiments. Then a parametric study was conducted to study the impacts of gas velocity, initial droplet velocity, droplet diameter, tower height, and initial solution temperature on the thermal performance of DSRUCT. According to the results of the parametric study, an optimization method called “critical height-gas velocity method” was proposed based on multivariable analysis. Two performance indicators, i.e., tower effectiveness and heat rate were used to evaluate the thermal performance of the DSRUCT. The optimization goal is to simultaneously ensure the thermal performance and save the initial investment of DSRUCT.

## 2. Mathematical model of DSRUCT

In this section, a mathematical model was developed to predict the performance of DSRUCT. As shown in Fig. 1, in DSRUCT, the cold solution was sprayed from the top of the tower. The sprayed droplets were forced to contact with an upward flowing gas stream. The solution temperature increased after absorbing heat energy from the gas. On the other hand, the gas was dehumidified and cooled as it flowed up.

A calcium chloride solution (16% mass concentration, freezing point - 12 °C) was adopted as the working liquid in DSRUCT in this study. The following assumptions were made during the calculation:

(1) Gas and droplet conditions are uniform and only change with vertical direction.
(2) Heat transfer through the wall of the DSRUCT is negligible.
(3) Solution concentration is constant during the process as the amount of water vapor is negligible compared with mass flow of the working fluid [9].
(4) No temperature gradient inside the droplets as the thermal resistance of the solution is negligible compared with that of the gas [25].

### 2.1. Governing equations

Energy, mass and momentum conservation laws were applied to DSRUCT to develop differential equations in a differential section of the tower height ($\Delta Z$). Five variables were considered during the heat and mass transfer process: solution temperature $T_s$, droplet velocity $u_d$, gas temperature $T_g$, droplet diameter $d$, and gas humidity $y$.

Applying Newton's second law [26] to a single droplet after neglecting the buoyancy, it follows that