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# Theoretical investigation and experimental verification of a mathematical model for counter-flow spray separation tower

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Despite the fact that the conventional one-dimensional model for counter-flow spray separation tower is advanced in reasonable accuracy as well as time and computational resources saving, it fails to describe the physical processes in details. In this paper, the concept of supersaturated state of the moist air was introduced, then a new sectional one-dimensional model was developed with a detailed derivation. A prototypic apparatus was set up and the reliability of the model was validated by the experimental study. When predicting the outlet solution temperature and outlet moist air wet bulb temperature, the relative errors would be more pronounced with a bigger heat and mass transfer driving potential, but they would not exceed 3.59% and 9.54% respectively under the experimental conditions. The simplifying assumptions, the ignored heat and mass transfer at cyclone region and the measuring errors are mainly blamed for the predicted errors. An in-depth heat and mass transfer investigation was conducted with the help of the validated model by studying the profiles of humidity ratio and moist air dry bulb temperature. The proposed model succeeded in capturing the state transformation of the air flow along the axis of the tower and the effects of the operating parameters on the process profiles are discussed.



## 1. Introduction

As the superiority of the relatively larger heat and mass transfer coefficients and area, the technology of atomization is widely applied in engineering applications with cooling towers, evaporators, condensers, chemical reactors and so on [1]. Spray evaporation, one of the atomization technologies, is carried out in a spray separation tower, in which the liquid phase is sprayed into small droplets by nozzles and then exchanges heat, mass and momentum with the gas phase simultaneously [2]. For the purpose of bone dry of the droplets, the gas phase usually functions as the thermal energy carrier to dry the droplets in the conventional spray separation tower [3,4]. In such devices, a high grade thermal source is required because of the poor specific heat of the air [5]. However, when the main duty of the spray separation tower is evaporation separation but not the bone dry of the droplets, the liquid phase working as the carrier to obtain thermal energy from the low grade thermal energy source is recommended. Because this type of spray separation tower is considered to be better efficiency and lower energy consumption [2]. This type of spray separation tower can be regarded as a cooling tower in which the heat and mass transfer area is extended by the nozzles instead of the packing. What difference between the cooling tower and the spray separation tower is that the main object of the spray separation tower is to separate the moisture from the droplets but not to cool the liquid phase.

The modelling of spray separation tower is universally acknowledged being a challenging task because of the complexity associated with the integration of the evaporation of the droplets with the interacting hydrodynamic and heat/mass and momentum transfer between the two phases [6,7]. Thus, the study of the spray separation tower was usually conducted based on the rules derived from experience with existing plants at the initial stage [8]. Owing to the development of CFD technology [9–13], it is exercisable to capture the physical processes in details in a comparatively rigorous way while this would be highly computationally intensive [8]. So it is highly desirable to have a model by which the design parameters are assessed toillessly. The one-dimensional model, a simpler one, has been widely employed [6,8,14,15]. Following the rules of this method, the tower is divided into numerous small regions along the vertical axis and the droplets and gas are considered to be flowing parallel to each other [6]. Truong et al. [15] developed a steady state one-dimensional model to describe the stickiness in co-current spray drying of sugar-rich foods. The prediction and measurement of

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**Nomenclature**

| | |
|---|---|
| $A$ | heat and mass transfer area [$m^2$] |
| $A_{fr}$ | section area [$m^2$] |
| $a_{fi}$ | specific surface area [$m^2/m^3$] |
| $B_m$ | Spalding mass transfer number [–] |
| $B_T$ | Spalding heat transfer number [–] |
| $C_D$ | drag coefficient [–] |
| $c_p$ | specific heat at constant pressure [$J\cdot kg^{-1}\cdot K^{-1}$] |
| $D_v$ | diffusion coefficient [$m^2\cdot s$] |
| $d_0$ | discharge orifice diameter [m] |
| $G$ | volume flow rate [$m^3\cdot h^{-1}/L\cdot h^{-1}$] |
| g | gravitational acceleration [$m\cdot s^{-2}$] |
| $h$ | heat transfer coefficient [$W\cdot K^{-1}\cdot m^{-2}$] |
| $h_d$ | mass transfer coefficient [$kg\cdot m^{-2}\cdot s^{-1}$] |
| $i$ | enthalpy [$J\cdot kg^{-1}$] |
| $i_{fgwo}$ | latent heat of vaporization [$J\cdot kg^{-1}$] |
| $Le_f$ | Lewis factor [–] |
| $m$ | mass [kg] |
| $\dot{m}$ | mass flow rate [$kg\cdot s^{-1}$] |
| $Nu$ | Nusselt number [–] |
| P | pressure [Pa] |
| $Pr$ | Prandtl number [–] |
| $\dot{Q}$ | heat transfer rate [W] |
| $r$ | radius [m] |
| $Re$ | Reynolds number [–] |
| $Sc$ | Schmidt number [–] |
| $SMD$ | Sauter mean diameter [m] |
| $Sh$ | Sherwood number [–] |
| $T$ | temperature [K/°C] |
| $t$ | time [s] |
| $v$ | velocity [$m\cdot s^{-1}$] |
| $Y$ | vapor concentration [$kg\cdot kg^{-1}$] |
| $z$ | height of the tower [m]/dimensionless height[–] |
| *Greek* | |
| $\theta$ | half spray angle [°] |
| $\mu$ | dynamic viscosity [Pa·s] |
| $\xi$ | mass concentration [%] |
| $\rho$ | density [$kg\cdot m^{-3}$] |
| $\sigma$ | surface tension [$N\cdot m^{-1}$] |
| $\omega$ | Humidity ratio [$kg\cdot kg^{-1}$] |
| *Subscripts* | |
| a | air |
| c | convective heat transfer |
| c1 | conventional model |
| c2 | sectional model |
| d | droplet |
| e | experiment/evaporation |
| H | pure water |
| i | inlet |
| m | average or mass transfer |
| o | outlet |
| us | unsaturated |
| sa | saturated |
| ss | supersaturated |
| sw | the saturated air at the droplet surface temperature |
| v | vapor |
| w | liquid phase |
| 0 | ambient or initial |

outlet air temperature agreed well under different operating conditions. Ali et al. [6] employed a one-dimensional model as well, with which a semi-empirical slurry droplet drying model was integrated, to predict the temperature and concentration profiles within a counter-flow spray drying tower. The results of the numerical model were compared with industrial pilot plant data and showed that the performance was significantly interrelated with the specified size distribution of the droplets. Sormoli et al. [8] found that the one-dimensional model was a rapid estimation method with good accuracy to predict the key parameters in the spray drying tower scale-up process.

The above analytical one-dimensional models [6,8,14,15] have been derived with the default that the moist air is always unsaturated along the spray separation tower because the moist air is the thermal energy carrier. But in the case of liquid phase being the thermal energy carrier, the moist air would become saturated before it leaves the tower in that the temperature of liquid phase is still higher than the temperature of the moist air, so the gradient for temperature and vapor concentration still exists at the moist air–droplet interface. Under these conditions, the excess water vapor will condense as a mist and be gotten entrained with the air flow. The saturated air with the condensed mist is the supersaturated state of air [16]. Kloppers and Kröger [16] reported that the Poppe method [17] was especially suitable to be employed in the heat and mass transfer analysis of the devices such as cooling tower, humidifier, spray separation tower, as this method took into account the supersaturation and the state of the outlet moist air was accurately determined. Zamen [18] developed a model based on Poppe method [17] for both unsaturated and supersaturated states to predict accurately the outlet conditions of the air and water streams in a cross-flow packed bed humidifier. The model was validated by experimental results and proposed to be employed in a designing mission. Zheng et al. [19] also implemented a method for heat and mass transfer analysis in a closed wet cooling tower based on Poppe method [17]. The thermal performance was investigated by a program which could automatically select the governing equations corresponding to states of the moist air. It showed that the state parameters of the moist air under both unsaturated and supersaturated conditions could be accurately predicted with the analytical models.

Although the conventional one-dimensional model possesses the advantages of reasonable accuracy as well as time and computational resources saving, it fails to capture the physical processes in details [7,8]. The Poppe method is competent to overcome this disadvantage of the conventional one-dimensional model when attempting to model the spray separation tower in which the liquid phase is the thermal energy carrier. In this paper, a sectional one-dimensional model for a counter-flow spray separation tower is developed based on Poppe method [17]. A prototypic spray separation tower is set up as well, from which the experimental results are compared with those given by the theoretical analysis under different operating conditions. Moreover, by means of the validated model, the heat and mass transfer processes are investigated by studying the profiles of humidity ratio and dry bulb temperature of the moist air along the axis.

## 2. Theoretical modelling

The available heat and mass transfer model for single droplet in the literature is introduced, and then the detailed derivation of the proposed sectional one-dimensional model of the spray separation tower is also presented by employing an approach similar to Poppe and Rögener model [17].