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Theoretical and experimental studies on a solid containing water droplet

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ABSTRACT

Heat and mass transfer to and from a single solution droplet is studied in this work. A new theoretical model to predict the evaporation behaviour of solid containing water droplets is presented. The model, implemented in MATLAB, is used to predict the process of droplet evaporation with prediction results successfully validated against data from the literature. Also, an experimental study was performed to study the evaporation of a single droplet containing NaCl and water. To investigate the influence of concentration, tests were performed with droplet having initial radiuses of approximately 0.5 mm and initial mass concentrations of 3% and 5%. Results obtained from the developed model were found to be in good agreement with our experimental data. Finally, it was shown that the current model, allowing for a smooth transition from surface evaporation to crystallisation, is able to simulate the process more accurately compared to existing models in the literature which lead to a, less realistic, sharp transition.

1. Introduction

Liquid sprays are widely applied in engineering applications with cooling towers, evaporators, condensers, and chemical reactors as some examples. The benefit of using these liquid sprays is increasing the contact area to obtain higher total heat and mass transfer between liquid and air. Applying this technique in arid areas, however, faces an obvious challenge of providing pure water. Hence, saline water is being used as an alternative in the spray-assisted dry (hybrid) cooling towers. Heat exchanger surfaces are in exposure of corrosion and deposit formation due to using saline water because of large amount of corrosive ions in water. Therefore, contact of solid containing water droplets in a hybrid cooling tower to the heat exchanger surfaces should be avoided. In other words, evaporation of the droplets should be completed before they reach the heat exchanger surfaces.

Beginning to evaporate, the evaporation rate of a solid-containing droplet is the same as that of pure water droplet. However, when the average concentration (mass fraction of the solid divided by the total mass of the droplet) reaches that of saturation, solid formation occurs leading to an increase in the droplet temperature [1]. This temperature rise is due to both heat of crystallisation and sensible heat transfer in the case of solutions, and to sensible heat transfer in the case of suspensions [1].

1.1. Review of existing evaporation models

1.1.1. Two-stage models

There are models in the literature that assume two stages for droplet evaporation. According to those models, during the first stage of evaporation the main component of the droplet is assumed to be water. The second stage begins when the solid content of the droplet increases, due to water evaporation, and goes beyond a critical concentration value [2].

Applying a two-stage model, Abuaf and Staub simulated the latter stage by assuming the droplet as a porous solid crust around a wet core at the centre [2]. Elperin and Krasovitov assumed quasi-steady evaporation and showed that the evaporating rate is highly dependent on the permeability of the formed porous crust for vapour and heat transfer [3].

1.1.2. Three-stage models

On top of two-stage models, some researchers showed that three different stages occur during evaporation of a solution droplet [3–6]. According to those authors, the first stage of the previous model is divided into two stages including: temperature adjustment stage and constant-temperature evaporation stage.

Three-stage models assume that the droplet temperature remains constant beyond the wet-bulb temperature. This isothermal stage is then followed by a sharp rise in the droplet temperature to reach the ambient air temperature. Also, a d^2 law is assumed for the time taken for the unset of crust formation [7]. A mathematical model was presented by Farid to predict the

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Nomenclature

A	surface area
B	Spalding number
c	concentration
c_p	specific heat
D_v	vapour diffusion coefficient
h	heat transfer coefficient
h_{fg}	specific heat of evaporation
Kn	Knudsen number
k	thermal conductivity
m	mass
$\dot{m}$	mass transfer rate
M	molecular weight
Nu	Nusselt number
p	pressure
Pr	Prandtl number
r	radial space coordinate
R	radius
$\mathcal{R}$	universal gas constant
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
t	time
T	temperature
V	volume
α	thermal diffusivity
β	empirical power coefficient
δ	volume fraction
ε	crust porosity
λ	molecular mean free path
ρ	density

Subscripts

cr	crust
d	droplet
g	gas
p	pore
s	solid
v	vapour
w	water
wc	wet-core
0	initial condition
∞	free stream

change of mass and temperature of a single milk droplet in contact with hot air in a spray drying [8]. A constant evaporation rate was assumed during the first stage of the process. This period could be very short which is related to the nature of the droplets. A considerable temperature rise was reported after the completion of drying stage [8].

Dalmaz et al. assumed that there is a pure water layer around spherical mixture of water and solid particles [6]. This water layer is evaporated during the first stage until very first solid particles come in contact with the surrounding air. The second stage begins at this point and evaporation continues by diffusion of vapour through the porous layer. On the other hand, Mezhericher et al. solved the governing equations for three stages of evaporation to find droplet temperature and mass assuming Stefan's tube for the porous crust [4]. According to those authors, during the second stage of evaporation the outer diameter of the droplet remains constant whilst the particle wet core shrinks. Also available in their report, is a review of theoretical models to study the evaporation of single solid-containing droplets [9].

It is known that after the third stage, first solid particles form at the bottom of the droplet [10]. As the evaporation continues, the solid crystals form around the droplet circumferential area. This is followed by phase change at the upper half of the droplet. It was reported that evaporation from the upper half of the droplet is faster compared to that from the lower half [10]. Nevertheless, this fact has not been considered in the mathematical modelling of the previous works.

Recent experimental studies on single droplet have been performed using thin filaments to hold the droplet. The temperature measurements of the droplet was done by using two thermocouples made of two different metals in the experimental study by Qi Lin and Chen [11]. The thermocouples were inserted inside the droplet in different runs from the ones for measuring the diameter and weight. They showed that the droplet would remained attached to the filament knob even after formation of solid parts [11]. Chew et al. used a glass filament method to measure the temperature, diameter and the moisture content (water to solid mass fraction) of the droplets [12]. The used glass filaments were coated with Rocol dry film Teflon spray to diminish the tendency of climbing or capillary effects. They also measured the droplet diameter by digital camera using Adobe after Effect 7.0 and droplet temperature using a connected thermocouple in two separate runs [12].

2. Theoretical modelling

The available theoretical models in the literature divide the evaporation of a solid containing droplet into two stages [2,13,14] or three stages [3–6]. First stage is temperature adjustment stage followed by size decrease in constant temperature (wet-bulb) in the second stage. In the third stage, solidification begins and droplet temperature reaches its maximum value. It is expected that the crust formation be a gradual process starting from the bottom of a droplet [1,2,8,10]. Commensurate with the existing experimental data in the literature, our current experimental study leads to similar observations as will be discussed later. Nevertheless, all of the available models lead to a sudden jump in the droplet temperature after the crust is formed. Thus, a transient stage is introduced in this work after the second stage to simulate the physical phenomena more realistically. It should be mentioned that since cooling tower representative condition are the main application of the current model, the conditions above the boiling points and fracture of the porous shell due to pressure rise of the gas–vapour mixture are outside of the scope of the current study. However, increase of saturated pressure due to temperature rise is being taken into consideration.

2.1. Stages of the evaporation for a solid containing water droplet

Fig. 1 categorizes saline water droplet drying based on their solid content and properties. During evaporation, the solid crystal forms at the lower part of the droplet and extends up to the droplet sides. NaCl has a porous and rigid structure after drying according to [10].

In view of the above, a process similar to that described by Fig. 1 is expected for the evaporation of a water + NaCl solution. Fig. 2 illustrates the different stages of evaporation for a solid-containing water droplet including the transient stage. As shown in this figure, in stage 3 a solid crust starts to form from the bottom of the droplet. Now, stages one, two, and four will be discussed followed by