



# A theoretical model with experimental verification for heat and mass transfer of saline water droplets



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## ABSTRACT

Heat transfer to and mass transfer from NaCl–water droplets are investigated both numerically and experimentally. A new model is presented and used to simulate saline water droplet evaporation. The model is robust enough to be applied for various initial concentrations and conditions of the droplet, ambient conditions, and dissolved media properties. The model is validated using experimental data obtained in this study on top of those already available in the literature. The experimental apparatus as well as the processing routines to optically measure droplet evaporation at a range of ambient conditions are presented. The droplet was suspended using a glass filament. Data were collected for droplets with an initial radius of 500  $\mu\text{m}$  at three temperatures 25  $^{\circ}\text{C}$ , 35  $^{\circ}\text{C}$ , and 45  $^{\circ}\text{C}$  and three air velocities 0.5 m/s, 1.5 m/s, and 2.5 m/s to provide a comprehensive validation dataset. Based on experimental and simulation data, a correlation is presented that captures the start time of solid formation. This time plays an important role in cooling tower design as it shows the time that the outer surface of the droplet dries. Using the validated model, it is shown that for 500  $\mu\text{m}$  radius droplets with 3% initial mass concentration the start time of reaching the final size is 17% less than evaporation time of a pure water droplet. Also, the net energy required to evaporate the droplet falls by 7.3% compared to a pure water droplet. For 5% initial concentration these values are 24.9% and 12.2%, respectively. Using saline water in spray-cooling has two major effects: the energy extracted from the air per unit droplet volume is reduced (which can be compensated for by increasing the liquid flow rate). Moreover, compared to the time taken for the evaporation of a pure water droplet, the period with wet surface is shorter as a result of crust formation around the saline water droplet. This allows a shorter distance between spray nozzles and heat exchangers.

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## 1. Introduction

Improving the efficiency of dry cooling towers has always been a challenge for designers. For instance, in arid areas production capacity losses of about 50% are predicted [1]. To enhance the performance of dry cooling towers, hybrid methods are suggested to decrease inlet air temperature. Two hybrid methods are available in dry cooling systems: evaporative spray cooling of the inlet air, and using water deluge to cool the air. Spray assisted dry cooling towers are more efficient and cost effective in arid areas as they do not require a large volume of water. With liquid spray cooling systems, the decreased cooling tower inlet air temperature leads to higher thermodynamic efficiencies. Here the spray removes heat

from the air approaching the heat exchangers inside the tower. As a result, the cold side temperature of the thermodynamic cycle is reduced. This reduction in temperature at which heat is rejected, increases overall thermodynamic efficiency.

Applying spray cooling in dry areas, however, faces an obvious challenge of fresh water scarcity. However, as an alternative, saline water might be available in spray-assisted dry cooling towers (hybrid). For example, in arid areas in Queensland, Australia a large volume of water is produced in the production of natural gas from coal-bed methane. Methane desorbs from coal if pressure is decreased in the underground reservoir by water pumping [2]. Therefore, saline water will be available as a valuable source for spray cooling systems. There are, nonetheless, some dissolved and insoluble materials in this water. Kinnon et al. showed that NaCl is the main salt in the saline water from coal-bed methane production [3]. According to those authors, NaCl constitutes about 84% (mass based) of the total dissolved salt in Bowen Basin in

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### Nomenclature

$A$	surface area ( $\text{m}^2$ )	$Sh$	Sherwood number
$B$	Spalding number	$St$	Stanton number
$c$	mass concentration	$t$	time (s)
$c_p$	specific heat ( $\text{J/kg K}$ )	$\bar{t}$	dimensionless time = $\frac{t_{4th\ stage} \dot{m} g}{m_{0,d}}$
$C_1$	constant in experimentally obtained correlation	$T$	temperature (K)
$D_v$	vapour diffusion coefficient ( $\text{m}^2/\text{s}$ )	$z$	weighting factor for transition to crust formation
$f$	experimental correlation	<i>Greek symbols</i>	
$h$	heat transfer coefficient ( $\text{W}/\text{m}^2 \text{K}$ )	$\beta$	empirical power coefficient
$h_D$	mass transfer coefficient (m/s)	$\varepsilon$	crust porosity
$H_{evap}$	specific heat of evaporation ( $\text{J}/\text{kg}$ )	$\Omega$	temperature ratio
$k$	thermal conductivity ( $\text{W}/\text{m K}$ )	$\rho$	density ( $\text{kg}/\text{m}^3$ )
$m$	mass (kg)	<i>Subscripts</i>	
$\dot{m}$	mass transfer rate (kg/s)	$cr$	crust
$\dot{m}$	mass flow rate (kg/s)	$d$	droplet
$M_w$	molecular weight (kg/mol)	$g$	gas
$Nu$	Nusselt number	$s$	solid
$p$	pressure (Pa)	$v$	vapour
$Pr$	Prandtl number	$wb$	wet-bulb
$r$	radial space coordinate (m)	$wc$	wet-core
$R$	radius (m)	$0$	initial condition
$\mathcal{R}$	universal gas constant ( $\text{J}/\text{mol K}$ )	$\infty$	free stream
$Re$	Reynolds number		
$RH$	relative humidity		
$Sc$	Schmidt number		

Queensland. Due to the similarities between the physical properties of NaCl and the other dissolved salts, NaCl may be considered as the main dissolved salt in saline water. A side effect of using saline water is that the heat exchangers are exposed to corrosion and solid particle (salt) deposition. Chloride ions in the water increases the rate of corrosion on the surface of the heat exchanger [4]. Therefore, contact of liquid and the heat exchanger surfaces should be avoided in a hybrid cooling tower. In other words, evaporation of the droplets should be completed before they reach the heat exchanger surfaces.

To simulate the evaporation process from solid-containing droplet, researchers have suggested two [5,6] and three-stage models [7–10]. In general, the evaporation of droplets can be described as follows (see Fig. 1):

1. The droplet is warmed/cooled to be close to ambient conditions.
2. Evaporation takes place during an isothermal phase.
3. First particles form at the bottom of the droplet [11] and grow to cover the upper part.
4. The remaining water is then evaporated followed by complete drying.

The slow formation of the crust is considered in the mathematical modelling by Sadafi et al. [12]. In their four-stage model they showed that the droplets shrink even after presence of solid particles on the surface which results in a better agreement with the experimental results compared to former models [12].

Handscomb and Kraft described a generalised model with different possible sub-models for evolution of the droplets following shell formation which includes slow boiling after dry shell formation [13,14]. They demonstrated that morphology of droplet plays a key role in the droplet evolution after shell formation. Under certain circumstances, a further isothermal stage may exist after shell formation [14].

Recent experimental studies on a single droplet have been performed using thin filaments to hold the droplet. Temperature measurements of the droplet were performed using two thermocouples in the experimental study by Qi Lin and Chen [15]. Those authors

measured the diameter and weight of skim milk droplets to show that droplets could remain attached to the filament knobs even after the formation of solid parts [15]. Chew et al. used a heated glass filament which was also used as a thermocouple to measure the (high solid concentration milk) droplets temperature [16]. Using a microscope digital camera, Sadafi et al. monitored the droplet size at low air velocities to note that the droplets shrink after crust formation in slow evaporation under standard room conditions [12].

## 2. Theoretical modelling

The four-stage model developed by Sadafi et al. [12] was used in this study and is briefly described in Section 2.1. This model and

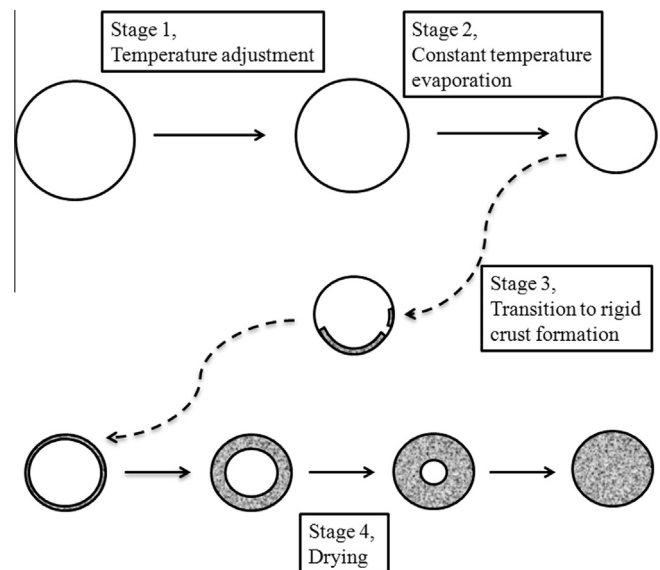


Fig. 1. Stage of evaporation of a solid containing water droplet.

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