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# Theoretical analysis of water film evaporation characteristics on an adiabatic solid wall

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ABSTRACT

A theoretical study was conducted to analyze the transient evaporation characteristics of water film attaching to an adiabatic solid wall, with its other surface exposed to moist air. An analytical solution for the heat conduction in water film with a combined sensible and latent heat transfer boundary condition at the water/air interface was provided, and the effects of water film thickness, water/air convective heat transfer coefficient, and air temperature on water film evaporation characteristics was investigated. The results show that when the water evaporation starts, the water surface temperature drops instantly, as time goes on, the water surface temperature declines continuously until it reaches the air wet-bulb temperature. The latent heat needed for the water evaporation comes mainly from the water film by heat conduction at the initial stage, but more from the air fluid by heat convection afterward, and entirely from the air fluid when the water temperature attains to the air wet-bulb temperature.

# Analyse théorique des caractéristiques d'évaporation d'un film d'eau sur une paroi solide adiabatique

*Mots clés :* Evaporation de film d'eau ; Paroi adiabatique solide ; Air humide ; Transfert de chaleur et d'humidité ; Solution analytique

## 1. Introduction

Water film evaporation phenomena widely exist in air conditioning, metallurgy, foundry, and petrochemical industries. Many studies have been done on water film evaporation in recent years. Li et al. (2011) performed an experimental study of falling water film evaporation on newly-designed enhanced tube bundles and investigated the influence of film Reynolds number on heat transfer coefficient and temperature on convective heat flux. Schwartze and Brocker (2000) studied water film evaporation in moist air with different humidities.

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**Nomenclature**

| | |
|---|---|
| $A$ | regression coefficient |
| $B$ | regression coefficient |
| $Bi$ | equivalent *Biot* number |
| $c_p$ | specific heat of water, J kg$^{-1}$ K$^{-1}$ |
| $c_{pa}$ | specific heat of air, J kg$^{-1}$ K$^{-1}$ |
| $h$ | convective heat transfer coefficient, W m$^{-2}$ K$^{-1}$ |
| $h_c$ | combined heat and mass transfer coefficient, W m$^{-2}$ K$^{-1}$ |
| $J$ | water evaporation rate, kg m$^{-2}$ s$^{-1}$ |
| $J_{01}$ | evaporation rate at unsteady stage, kg m$^{-2}$ s$^{-1}$ |
| $J_{12}$ | evaporation rate at steady stage, kg m$^{-2}$ s$^{-1}$ |
| $k$ | convective mass transfer coefficient, kg m$^{-2}$ s$^{-1}$ |
| $L$ | latent heat of evaporation of water, kJ kg$^{-1}$ |
| $Le$ | Lewis number |
| $q_d$ | conductive heat flux, W |
| $q_L$ | latent heat flux, W |
| $q_v$ | convective heat flux, W |
| $T$ | temperature, K or °C |
| $T_0$ | initial system temperature, bulk air temperature, K or °C |
| $T_{wb}$ | wet-bulb temperature of bulk air, K or °C |
| $t$ | lifetime of water film, minute |
| $w$ | humidity ratio of saturated moist air, kg kg$^{-1}$ |
| $w_0$ | humidity ratio of bulk air, kg kg$^{-1}$ |

*Greek letters*

| | |
|---|---|
| $\phi_0$ | relative humidity of bulk air |
| $\mu_n$ | parameter for transcendental equation |
| $\delta$ | water film thickness, mm |
| $\tau$ | time, s |
| $\tau_1$ | time limit of unsteady stage, s |
| $\tau_2$ | time limit of steady stage, s |
| $\delta_0$ | initial water film thickness, mm |
| $\rho$ | density of water, kg m$^{-3}$ |
| $\rho_a$ | density of air, kg m$^{-3}$ |
| $\lambda$ | heat conductivity of water, W m$^{-1}$ K$^{-1}$ |

Raimundo et al. (2014) numerically simulated water film evaporation in airstream and discussed the effects of air velocity, water–air temperature difference and air relative humidity on the evaporation rate. Yang and Yan (2011) and Yu and Wang (2012) studied water film evaporation on solid surfaces using molecular dynamics simulation method. Leu et al. (2006) experimentally investigated water film evaporation on a vertical plate covered with a thin porous layer and found that such a layer enhanced the heat and mass transfer during the evaporation process. In addition to the studies on the water film evaporation, there are also studies that have focused on the water droplet evaporation (e.g., Lee et al., 2012; Deendarlianto et al., 2014; Nakoryakov et al., 2012; Takata et al., 2004).

Water evaporation into ambient air is generally treated as a steady process in engineering, with the water temperature being assumed to be the wet-bulb temperature of the air fluid. There is little research on the unsteady characteristics of water film evaporation on an adiabatic solid wall. The present research seeks to analyze the transient water film evaporation in moist air and to investigate the effects of water film thickness, water/air convective heat transfer coefficient, and air temperature on water film evaporation characteristics. The uniqueness of this research is to provide an analytical solution for the transient heat conduction in water film with a combined sensible and latent heat transfer boundary condition at the water/air interface and bring about a theoretical analysis of the water film evaporation characteristics based on the solution.

## 2. Theoretical model

Consider the one-dimensional water film evaporation process shown in Fig. 1. The water film attaches to an adiabatic solid wall, with its other surface exposed to moist air. It has an initial temperature of $T_0$ and an initial thickness of $\delta_0$. The moist air has a temperature of $T_0$ and a relative humidity of $\phi_0$, which is less than unity. The convective heat transfer coefficient between the water surface and the air fluid is $h$. The figure also shows the coordinate system, $x$, which has an origin at the solid wall surface and points to the water film thickness direction.

Assuming that the water and air both have constant physical properties, the equation governing the heat conduction in the water film can then be represented by

$$\rho c_p \frac{\partial T}{\partial \tau} = \lambda \frac{\partial^2 T}{\partial x^2} \tag{1}$$

As the initial condition at $\tau = 0$:

$$T = T_0 \tag{2}$$

As the boundary condition at the solid wall/water film interface at $x = 0$:

$$\frac{\partial T}{\partial x} = 0 \tag{3}$$

further, at the water film/air fluid interface at $x = \delta$:

$$q_d + q_v = q_L \tag{4}$$

where

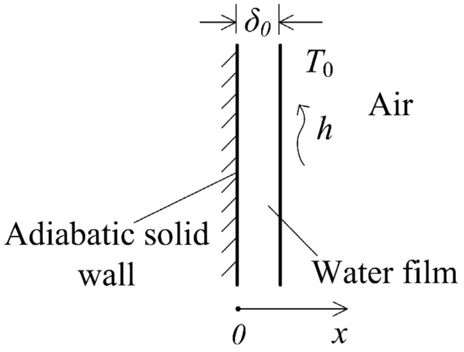

**Fig. 1 – Schematic of water film evaporation on an adiabatic solid wall.**