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Theoretical derivation and comparative evaluation of mass transfer coefficient modeling in solar distillation systems – The Bowens ratio approach

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Abstract

In the present investigation a group of mass transfer coefficient expressions was derived based on the definition of Bowen's ratio as applied on a properly modified diffusive interface model, under specific assumptions which impose the restrictive conditions for application in solar distillation systems. These conditions determine the validity range of the derived expressions that include Dunkle's mass transfer models, which as it was recently derived by extensive experimental evidence although are sufficiently accurate at ordinary fail at higher operating temperatures. Based on the developed analysis it was found that this is mainly attributed to the full account of partial water vapor pressures and the neglecting of induced flow enhancement phenomena, which decisively influence the mass transfer as the operating temperature increases. It was also derived that the impressive accuracy of the Chilton–Colburn model, which has been experimentally validated at a broad range of operating conditions, is basically attributed to the complete lack of specific restrictive assumptions. These, combined to the proper account of Lewis number for saturated mixtures as well as the appropriate consideration of mass transfer enhancement phenomena at higher operating temperatures, contribute to the development of an accurate mass transfer model of a more universal nature, suitable for application at a broad range of operating conditions.

Keywords: Solar distillation; Mass transfer coefficient; Bowen's ratio

1. Introduction

Solar distillation is a vital technology to support the survival of human offshore and isolated island communities in arid and semi-desert geographical zones. Although a substantial amount of research and development work has been carried out during the last few decades on solar distillation systems that has been earlier reviewed extensively, Tiwari et al. (2003), the research activity is still sustained by advanced contributions as derived by recent publications in the literature, Rahbar and Esfahani (2013), Alvarado-Juarez et al. (2013), Vieira da Silva et al. (2013).

The effectiveness of this technology basically relies on the efficiency of the evaporation and condensation cycle which occurs during the operation of solar distillation systems of almost any design. The accurate modeling of this cycle is a matter of substantial importance for the design optimization and performance prediction of these environmentally friendly energy systems.

The study of evaporation began to emerge since Dalton first discovered fundamental laws, while publications of many subsequent investigators have developed the scien-

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Nomenclature

A	surface area (m^2)
Bo	Bowen's ratio (–), $\mathrm{Bo} = \frac{Q_{cv}}{Q_e}$
c_p	specific heat capacity (J/kg K)
C_o	dimensional numerical constant (K^{-1})
C_B	dimensional numerical constant (Pa K^{-1})
d	equivalent thickness (m)
D	diffusion coefficient (m^2/s)
h	heat or mass transfer coefficient (w/m^2 K)
h_{fg}	heat of evaporation (kJ/kg)
k	thermal conductivity (w/m K)
L	distance, length (m)
Le	Lewis dimensionless number, $\mathrm{Le} = \frac{a}{D_v}$
$\dot{m}$	per unit surface area mass flow rate (kg/m^2 s)
M	molar mass (kg/kmol)
Nu	Nusselt dimensionless number, $\mathrm{Nu} = \frac{L \cdot h}{k}$
P	pressure (Pa)
P_o	barometric pressure, $P_o = 101.3 \times 10^3$ Pa
P_{LM}	logarithmic mean pressure (Pa), $P_{LM} = \frac{(P_o - P_{vs}) - (P_o - P_{vg})}{\ln \frac{P_o - P_{vs}}{P_o - P_{vg}}}$
P_o/P_{LM}	drift or blowing factor (–)
R	gas constant (kJ/kg K)
$\mathfrak{R}$	universal gas constant, $\mathfrak{R} = 8.314$ kJ/kg K
t	temperature (°C)
T	absolute temperature (K)
$\bar{t}$	average temperature, (°C), $\bar{t} = \frac{t_w + t_g}{2}$
ΔT	temperature difference (°C or K), $\Delta T = T_w - T_g = t_w - t_g$
z	compressibility factor (–)

Greek letters

α	thermal diffusivity (m^2/s), $\alpha = \frac{k}{\rho . c_p}$
Δ	difference
ρ	density (kg/m^3)

Subscripts

a	air
cv	convective
e	evaporative, mass
g	glazing
LM	logarithmic mean
m	mixture
s	surface
v	vapor
w	water

tific background of the evaporation theory applied to natural water bodies which is a crucial issue for the proper water management and it considerably affects the climate that determines the environment in earth, Bowen (1926), Deacon et al. (1956), Magin and Randall (1960). Among these, Bowen (1926), attempted in his pioneering work to evaluate the sensible to latent energy transfer ratio, aiming to calculate the latent heat transfer and evaporation rate from extended natural water bodies based on energy balance considerations. Having adapted this theory, Dunkle (1961) developed a broadly established mass transfer model to predict the transport processes in solar distillation systems, according to which,

$$\frac{h_e}{h_{cv}} = \frac{h_{fg}}{c_{pa} \cdot P_o} \cdot \frac{R_a}{R_v} \tag{1}$$

The previous expression is based on the assumption of negligible partial water vapor pressures and originally involves thermophysical properties corresponding to dry air. However at higher temperatures where partial water vapor pressures cannot be neglected, this ratio becomes strongly dependent on temperature,

$$\frac{h_e}{h_{cv}} = \frac{h_{fg}}{c_{pa}} \cdot \frac{R_a}{R_v} \cdot \frac{P_o}{(P_o - P_{vs}) \cdot (P_o - P_{vg})} \tag{2}$$

This early theory which has been extensively employed during the past several decades was proved to be extremely useful as a design and performance prediction tool and strongly influential in the solar distillation community, since it was broadly employed and repeatedly acknowledged in the literature by several subsequent publications Malik et al. (1982), Tsilingiris (2007), Tiwari and Tiwari (2008).

Owing to the fact that the majority of ordinary applications refer to field installations operating at low and medium temperature levels, it is not difficult to explain the extensive use of a fixed numerical value in the place of the (h_e/h_{cv}) ratio as derived from (1) for usual calculations instead of the value derived from (2). This value, although it varies slightly with temperature, can be estimated close to $(h_e/h_{cv}) = 0.01484$ for $h_{fg} = 2382.8$ kJ/kg at 50 °C and $P_o = 101.3$ kPa. Taking into consideration the appropriate values of the different involved parameters Tiwari et al. (1982) and Malik et al. (1982), initially derived a fixed value of $(h_e/h_{cv}) = 0.013$. However, since they realized that this value was lower than earlier evaluations by Bowen (1926) and Dunkle (1961), inferring possible reasons which may be attributed to the neglecting of the partial pressure terms, they recommended that the best representation of the heat and mass transfer phenomena is obtained if $(h_e/h_{cv}) = 0.016273$, a value that has broadly been employed for ordinary applications, Tiwari et al. (2003), Rubio et al. (2000), Sakthivel et al. (2010), Zurigat and Abu-Arabi (2004), Shawaqfeh and Farid (1995).

Although the accuracy of mass transfer model (1) has been proved to be mostly adequate for ordinary operating conditions, it has been sporadically reported in the litera-