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Combined heat and mass transfer analyses in solar distillation systems – The restrictive conditions and a validity range investigation

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Abstract

The present work aims at the investigation of the validity range and accuracy of earlier developed theories which have been proposed for the modeling of heat and mass transfer within confined spaces in solar distillation systems. The investigation which is based on the evaluation of agreement between theoretical results and an extensive body of earlier field and laboratory measurements covers a very wide range of operating conditions and allows a comparable validation of the earlier proposed theories. It also clearly defines the restrictions, limitations and the validity range in relationship to yield as well as to the operating temperature level, beyond which significant deviations between predictions from both the earlier Dunkle's as well as more recent analogy models and measurements occur for practical solar stills.

Keywords: Solar distillation; Mass transfer; Evaporation heat transfer; Transport processes modeling restrictions

1. Introduction

Seawater desalination is an energy intensive process that is best adapted to the solar energy resources. Solar distillation systems being currently considered as a mature technology may turn out to be vital for the survival of certain island and isolated offshore communities in close to equator arid and semi arid zones. These systems are basically composed of a top glazed cavity containing a saline water layer, which is heated by the transmitted solar radiation through the top glazing cover. This causes water heating, evaporation and transfer of water vapor from the liquid surface through a thin diffusive interface to a uniformly mixed layer of saturated air mixture. The flow of heat and water vapor from this layer through a similar diffusive interface at the top inner glazing surface causes condensation of water vapor, heat rejection and continuous outflow of distillate. When these fundamental processes are carried out once, with the sense that the overall upwards heat flux is directly rejected to the environment, the system can be seen as a single effect unit. When the process is successively repeated in a series of similar single effect units, which recover and reemploy the rejected heat, the systems are usually referred to as multi effect units. In either case, the modeling and prediction of the mass outflow in a typical single effect unit is a matter of a prime importance and depends on the precise evaluation of various complex physical processes, which determine the accuracy of yield prediction of any solar distillation system.

Several decades have passed since Dunkle (1961) first reported results from a complete theoretical analysis on the prediction of combined transport processes within the solar still enclosure of solar distillation systems, which was later discussed in greater detail by Malik et al. (1982). A substantial amount of both theoretical and

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Nomenclature

A_0 to A_4	numerical constants
c_p	specific heat capacity (J/kg K)
C	numerical constant
C_1 to C_3	numerical constants
D	diffusion coefficient (m^2/s)
DA_0 to DA_2	numerical constants
g	acceleration gravity (m/s^2)
Gr	grashof dimensionless number
h	heat (w/m^2 K) or mass (m/s) transfer coefficient
h_{fg}	heat of evaporation (kJ/kg)
HF_0 to HF_1	numerical constants
K	thermal conductivity (w/m K)
L	characteristic length (m)
Le	Lewis dimensionless number
$\dot{m}$	per unit still area mass flow rate (kg/m^2 s)
M	molar mass (kg/kmol)
n	numerical exponent
Nu	Nusselt dimensionless number
P	pressure (kPa)
Pr	Prandtl dimensionless number
R	gas constant (kJ/kg K)
Ra	Rayleigh dimensionless number
Ra^*	modified dimensionless Rayleigh number
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), $\Delta T = T_w - T_g = t_w - t_g$

Greek letters

α	thermal diffusivity (m^2/s)
β	coefficient of volumetric thermal expansion (K^{-1})
Δ	difference
μ	viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ξ	dimensional constant (K/Pa)
ρ	density (kg/m^3)

Subscripts

a	air
cv	convective
e	evaporative, mass
g	glazing
LM	logarithmic mean
m	mixture, average
ms	measured
o	total, barometric
p	predicted
w	water, brine

experimental work has been carried out during the last decades, aiming to acquire a deeper insight on the complex heat and mass transfer processes within the solar still enclosure like those by Kumar and Tiwari (1996), Tiwari et al. (1997), Porta-Gandara et al. (1998, 2004) and to improve the level of confidence on the developed theory as reported by Adhikari et al. (1990), Hongfei et al. (2002), Tiwari et al. (1998) and Tsilingiris (2009, 2011). Except for certain controversial reports that have sporadically appeared in the literature, it is impressive that this theory appears to be successful when it is applied under the appropriate assumptions. Aiming to extend the validity range and improve the prediction accuracy of physical processes, attempts have also been made to develop more universal models mainly based on the heat and mass transfer analogy approach. Shawaqfeh and Farid (1995) have reported an analogy model based on a purposely derived Rayleigh number correlation, which, although it developed overprediction of measurements, was employed for the evaluation of mass transfer in laboratory solar stills. Hongfei et al. (2002) have also developed a theoretical model based on analogy principles, which was properly validated by laboratory measurements at higher temperatures, while Tsilingiris (2010) has recently reported a Chilton–Colburn model which may be proved to be accurate in a broad range of operating conditions and temperatures. The present work aims to define the application restrictions and determine the suitability of the theory originally developed by Dunkle, for predictions in relationship to the wide yield and broad average temperature level range during the operation of solar distillation systems. The investigation also aims to specify the validity range and to underline the limitations of this analysis, to the best of the author's knowledge for the first time at such systematic level, based on extensive experimental evidence mainly relevant to usual operating conditions corresponding to strong turbulence in the solar distillation enclosure. Finally, the present work aims to apply, comparably validate as well as define the accuracy limitations of a Chilton–Colburn analogy model earlier developed by Tsilingiris (2010) for mass transport predictions at a wide range of operating conditions, based on extensive measurements from earlier reports in the literature and more recent field investigations carried out under typical Mediterranean mid summer climatic conditions.

2. The modeling of convective heat transfer in solar distillation systems

The flow of air and water vapor mixture under the effect of a destabilizing temperature gradient in any enclosed