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Parameters affecting the accuracy of Dunkle's model of mass transfer phenomenon at elevated temperatures

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HIGHLIGHTS

- Mass transfer modeling accuracy in solar distillation systems.
- Restrictive conditions for use of Dunkle's and Chilton–Colburn mass transfer models.
- Derivation of Dunkle's and Chilton–Colburn models based on Bowen's ratio.
- The importance of parameters affecting mass transfer modeling at higher temperatures.

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ABSTRACT

The accurate evaluation of combined transport processes is an issue of vital importance in solar distillation systems. The amount of condensed water vapor, being determined by the energy exchange between the brine and condensing surface, depends on both diffusion and bulk mass transport owing to natural convection phenomena occurring within the specific enclosed space geometry of any distillation unit. In the present investigation, the parameters affecting the modeling accuracy which determine the limitations under which the broadly established Dunkle's model is applicable are being investigated, comparably to the respective accuracy of the recently proposed Chilton–Colburn analogy model. The developed analysis allowed the investigation of the modeling deficiencies highlighting the reasons of degraded accuracy of the Dunkle's mass transfer modeling at elevated temperatures typically higher than about 55 °C, something that was recently indicated by comparative investigations based on extensive experimental evidence. It was found that this was mainly attributed to the omission of parameters which properly define the significant influence of mass transfer enhancement phenomena owing to the induced flow at higher operating temperatures, at which also the proper consideration of transport properties and Lewis number for the saturated mixture become factors of growing importance.

1. Introduction

Solar distillation is currently considered as a mature technology that has been developed over the last decades, during which a considerable amount of research, development and demonstration work was carried out. This work has been extensively reviewed in earlier and more recent publications such as Lof [1] and Velmurugana and Srithar [2]. Among its undisputable advantages are the use of environmentally safe solar energy in geographical regions at which not only it is abundant but it also occurs with maximum intensity at periods of peak water demand and the relatively low technology and resources required for the construction and operation of relevant systems.

With reference to ordinary passive single or double sloped solar stills as shown in Fig. 1a and b respectively, the incident solar radiation is partially transmitted through the top, slightly inclined glazing surface before being absorbed at the underlying horizontal layer of brine, sitting at the bottom of a properly thermally insulated cavity enclosure. This causes the heating of brine and the development of a vertical temperature gradient which is responsible for overall heat losses that are a contribution of natural convection, radiation and evaporation losses Q_{cv}, Q_r and Q_e respectively, from the free liquid to the top glazing surface at a lower temperature.

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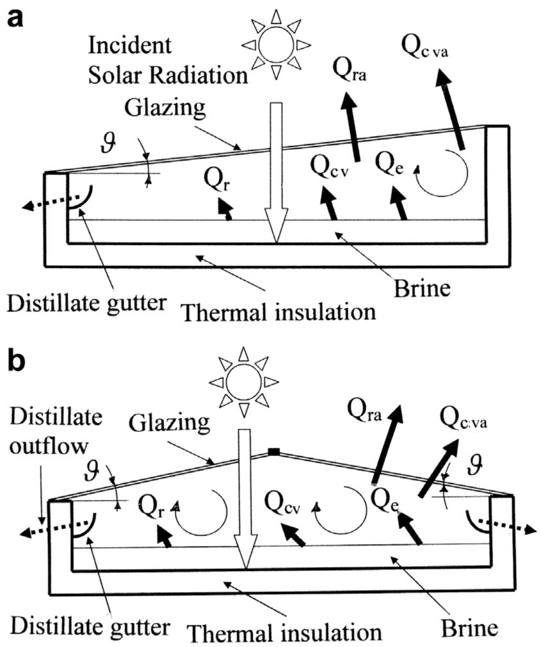

Fig. 1. Basic, single effect passive solar still design with a single (a) or double (b) sloped glazing and usual orthogonal cavity enclosures for small sloping angles, typically $\beta < 15°$.

Based on steady state experimental investigations inside a single slope solar still laboratory model, overall heat transfer coefficients up to about 650 W/m^2 were measured by Porta Gandara et al. [3]. Natural convection losses in an enclosed space between two horizontal plates corresponding to the fundamental design of passive solar stills has been the subject of detailed earlier investigations that have extensively been reviewed by numerous publications e.g. in Tsilingiris [4]. Although the calculation of thermal radiation losses between brine and glazing surface is usually based on the assumption of unity view factor value, recent investigations by Madhlopa [5] indicated that its proper evaluation is responsible for lower radiation heat transfer coefficient and associated losses, something which leads to the prediction of slightly higher yields.

The development of temperature causes a respective water vapor density gradient that drives an evaporation and condensation cycle during which the water vapor flows from the brine to the inner top glazing surface at which it condenses, rejecting the heat of condensation Q_e. The condensate outflows the cavity enclosure through the distillate gutter as pure water.

This design corresponds to a single effect solar distillation unit, in which the overall amount of sensible and latent heat transfer at the inner glazing surface is dissipated into the environment through forced convection Q_{ca}, and radiation Q_{ra} heat losses.

However, partial recovery of the rejected heat can eventually be employed to drive a number of subsequent single effect units in series before being finally dissipated into the environment. This heat recovery concept is extensively employed for the development of multi effect design of solar distillation systems and the technology is currently applied not only for large units but also for the design of small and efficient plants like those reported by Joo and Kwak [6], employing low grade heat from active solar collectors as energy input to the system. In principle the operation of passive multi effect solar distillation systems is shown in Fig. 2, comparably to the basic passive single effect unit design representing a conventional solar still. Under these conditions the rejected heat of a previous unit is exploited to drive the next evaporation and condensation cycle in each of the subsequent single effect units in series. This improved design leads to highly increased performance although not without a serious sacrifice of the basic solar still design simplicity and low initial cost.

The operation of these systems, which is similar to the hydrological cycle as it occurs in the atmosphere, is based on the efficiency of the associated transport processes. This cycle, which takes place during the evaporation and condensation of water vapor under barometric conditions, occurs in any solar distillation system, ranging from the basic passive solar stills to multi effect systems of advanced design.

The evaporation is a phenomenon of primary importance for the development of the climate and the water balance, which has concentrated a substantial degree of attention from the international scientific community since its very early stages of development. Aiming to investigate the evaporation from the free surface of natural water bodies based on energy balance considerations, Bowen [7] attempted in his earlier pioneering work to define and evaluate the sensible to latent energy transfer ratio. His analysis has been of decisive importance for the advancement of the environmental physics and very influential for water management applications in several scientific fields like agrometeorology and hydrology.

Based on the earlier scientific background on transport phenomena, Dunkle [8] was the first to report briefly in a Conference Proceedings publication the results of an analysis specifically dedicated to the combined transport processes associated with solar distillation. A more extensive description of this analysis was also later reported by Malik et al. [9]. Although the validity of this model appears to be sufficiently accurate for applications up to about 55 °C, substantial deviations were derived at higher temperatures, according to laboratory steady state measurements by Clark [10]. These results were confirmed by subsequent similar measurements by Adhikari et al. [11], using electrical power as energy input in laboratory simulated experiments and Tiwari et al. [12], who carried out steady state validating measurements employing a suitable laboratory solar still model based on an electrically heated constant temperature bath. It was later derived that these indications are strongly supported by further validation work which was carried out by Tsilingiris [13], based on a database of measurements from the literature covering a wide range of operating conditions.

Aiming to investigate the reasons for reduced accuracy at higher operating temperatures, subsequent analyses investigated the effect of moist air thermophysical properties as derived independently from simple linear mixing calculations [14] and molecular considerations [15]. Although the evaluation of saturated mixture properties was based on completely different approaches, the derived results were found to be almost identical. It was found that the proper use of saturated mixture properties leads to a slight decrease of mass transfer rates, which however, cannot adequately explain the reasons of the model failure at higher temperatures. An alternative, more universal mass transfer model based on the Chilton–Colburn analogy was recently proposed by Tsilingiris [16]; it appears to be suitable for application for a broad range of operating temperatures.

As derived from the previous discussion the thorough understanding and accurate prediction of the combined energy and mass transfer processes which occur inside an enclosed space representing a single effect, or within a number of such spaces comprising more efficient multi effect units, is crucial for their design optimization and reliable economic assessment. Although for small top glazing inclination angles this space becomes close to orthogonal, its geometry may sometimes become very complex,