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Analysis of the heat and mass transfer processes in solar stills – The validation of a model

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Abstract

The outcome of the earlier systematic research work on the theoretical modeling of the complex transport phenomena occurring in solar stills was the development of the fundamental Dunkle's model, already known almost four decades ago. Although it has been based on several simplified assumptions, this model has extensively been employed over the years as a convenient and sufficiently accurate predictive tool for solar stills working under ordinary operating conditions. However, it has occasionally been reported that it fails under unusual operating conditions, mainly corresponding to higher average temperatures, usually leading to higher distillate yields. The aim of the present investigation was to relax the initially established simplified assumptions of the fundamental Dunkle's model and to evaluate the comparative accuracy of both, the refined and the earlier fundamental models against an extensive body of previously reported measurements from the literature, both field and laboratory. The comparative presentation of results indicates that although both models are impressively correct for ordinary low temperature operating conditions where the humid air thermophysical properties are close to those of dry air, the saturation vapor pressure at the brine and condensing plate temperatures are negligible compared to barometric pressure and the familiar Jakob's dimensionless Nusselt–Rayleigh correlation for natural convection heat transfer appears to be valid, they both fail at higher operational temperatures. It appears that as far as Dunkle's simplified model is concerned, this occurs not only owing to the first two counteracting effects but also to the effect of the dimensionless convective heat transfer correlation affecting also the accuracy of the refined model, which fails to predict precisely the natural convection conditions at higher Rayleigh numbers representing conditions of strong turbulence in the solar still cavity. Assuming a constant asymptotic value of the exponent $n = 1/3$ which persists over a broad region of high Rayleigh numbers relevant to solar still operation, an improved value of the proportionality constant C around the value of 0.05 was estimated for the accurate prediction of measurements, at least as far as the available data from the literature is concerned.

Keywords: Convective heat transfer correlations

1. Introduction

Thermal processes for the distillation of seawater are known to be among the first technologies adapted to exploit solar energy. The idea of saline water evaporation by using thermal energy and its subsequent condensation for freshwater production was empirically applied several centuries ago to simulate the atmospheric air humidification and dehumidification during the hydrologic cycle. However, serious considerations for employing solar distillation applications in several regions of the world began not earlier than almost six decades ago, which led into the first systematic efforts towards accurate description of the basic interrelated transport phenomena involved during the distillation process (Telkes et al., 1955) and to intense experimental activities and full scale demonstrations (Lof, 1980; Cooper, 1969; Cooper and Read, 1974). Dunkle (1961) was the first to present a complete mathematical formulation and a fundamental theoretical model for the pre-

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Nomenclature

c_p	specific heat capacity (J/kg K)
C	numerical constant
$CA_1,\ldots,CA_4$	numerical constants
F	quantity defined by the expression (16)
g	=9.81 m/s^2 acceleration of gravity
h	heat transfer (W/m^2 K) or mass transfer (m/s) coefficient
h_{fg}	heat of evaporation (kJ/kg)
Gr	Grashof number (–)
k	thermal conductivity (W/m K)
$K_1,\ldots,K_3$	numerical constants
L	characteristic length (m)
M	molecular weight (kg/kmol)
m	numerical constant
$\dot{m}$	mass flow rate (kg/m^{2}s)
$MU_1,\ldots,MU_4$	numerical constants
n	numerical exponent
P	pressure (Pa)
Pr	Prandtl number (–)
q	heat flux (W/m^2)
R	gas constant (kJ/kg K)
Ra	Rayleigh number (–)
$RO_1,\ldots,RO_3$	numerical constants
t	temperature (°C)
T	absolute temperature (K)
T^*	equivalent temperature (K)
$\overline{T}$	average absolute temperature (K)
$TD_1,\ldots,TD_4$	numerical constants

Greek letters

α	thermal diffusivity (m^2/s)
β	volumetric expansion coefficient (°K^{-1})
θ	inclination angle (deg.)
ξ	numerical constant defined by the expression (28)
ΔT	temperature difference (°C)
ΔT^*	equivalent temperature difference (°C)
μ	viscosity (N.s/m^2)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

a	air
cv	convective
e	evaporative
g	condensing surface
m	mixture
o	total
s	liquid interface
v	vapor
vg	water vapor at the condensing surface
vs	water vapor at the liquid surface
w	distillate

diction of heat and mass transfer processes in solar stills. This analysis was based on the description of the free convection heat transfer in the solar still enclosure based on the familiar dimensionless correlation $Nu = 0.075Ra^{1/3}$, for upward heat flow in horizontal enclosed air spaces, as reported by McAdams (1958). Rheinlander (1982) developed an alternative numerical model for the solution of the heat, mass and momentum transfer equations in the still enclosure and derived results which were successfully compared with earlier work by Cooper (1973) and Kumar and Tiwari (1996). A subsequent simplified analysis which appears repeatedly in the literature was also presented by Malik et al. (1982), based on similar simplified assumptions by Dunkle, leading to basic heat and mass transfer correlations, which were also alternatively derived using Lewis relation. A substantial number of theoretical and experimental investigations have also been carried out during the last few decades, which have strongly contributed to the better understanding of the various combined heat and mass transfer processes in solar stills.

Adhikari et al. (1990) has carried out evaporation measurements in a laboratory environment for a very wide range of pool temperatures. Tiwari and Lawrence (1991) attempted to apply an improved Nusselt convective transport correlation while Shawaqfeh and Farid (1995) have carried out indoor and outdoor measurements aiming at comparisons with corresponding theoretical predictions. Further extensive field and laboratory measurements in passive and active solar stills have also been carried out (Kumar and Tiwari, 1996; Tiwari et al., 1997; Aggrawal and Tiwari, 1998) aiming to derive new improved accuracy values of the numerical constants in the dimensionless Nusselt number correlation based on regression analysis. Subsequent field investigations employing a passive solar still design of unusually large cavity dimensions were also conducted by Voropoulos et al. (2000) at low temperature levels, while careful laboratory measurements at a wide temperature range employing a metallic tray laboratory rig was conducted by Hongfei et al. (2002) aiming to establish improved heat transport correlations. The effect of considering the inner condensing plate surface temperature measurements for the derivation of appropriate heat transfer correlation model parameters was also investigated by Tiwari et al. (2003). The concept of solar fractionation was introduced and the investigation of the brine layer depth effects on heat and mass transfer conditions occurring in passive and active stills have also been recently investigated (Tripathy and Tiwari, 2004, 2005, 2006; Tiwari and Tiwari, 2006), while the effect of the condensing plate slope angle on the heat and mass transport processes was also experimentally investigated in the laboratory by Tiwari and Tiwari (2005). The effect of humid air thermophysical properties seen as a saturated binary mixture of water vapor and dry air on the heat and mass transport processes in solar stills was also investigated by Tsilingiris (2007), while findings from combined theoretical and experimental investigations have indicated a multi-parametric brine depth and condensing cover material dependence on the daily yield of an active solar still based on inner glass surface temperature data (Dimri et al., 2008).

These investigations led to a massive body of published, both field and carefully controlled laboratory measurements which are available from the literature, covering a variety of systems operating under various climatic conditions and technology environments under a wide range of operating temperatures. However, it has occasionally been reported that calculation results from earlier developed analyses and theoretical predictions cannot always be adequately supported by corresponding measurements, while objections have also been raised sporadically about the predictive accuracy of the fundamental Dunkle's model (Clark, 1990). The aim of the present investigation is to describe a more refined and improved accuracy model, allowing the relaxation of several simplified assumptions made by Dunkle in his original model and the comparative evaluation of these models against a massive body of available experimental evidence, based on the development of an extensive database of measurements derived from earlier published reports in the literature from field and laboratory investigations.

2. Theoretical modeling

The passive solar still of a conventional design is basically a sealed enclosure containing a shallow body of uniform temperature brine, which is heated by absorption of the solar radiation admitted through the top transparent condensing glass pane. The convective circulation of humid air, which is induced by the temperature differential between brine and the top condensing glass plate, causes the transport of water vapor from the brine surface to the top transparent glass pane where it condenses to the distillate outflow stream. While the driving force for the natural convective circulation in ordinary thermal systems is proportional to this temperature differential, the difference of water vapor content which is lighter than dry air between two regions of humid air mixture at different temperatures enhances markedly this driving force. According to Coulson and Richardson (1961) this can be taken into consideration by the definition of the modified Grashof number

$$Gr^* = \frac{g \cdot L^3}{v_m^2} \cdot \left(\frac{\rho_{\mathrm{m,g}}}{\rho_{\mathrm{m,s}}} - 1 \right), \quad (1)$$

where $\rho_{\mathrm{m,s}}$ and $\rho_{\mathrm{m,g}}$ the saturated mixture density at the region of the free brine surface and the top condensing plate at temperatures T_{s} and T_{g}, respectively. Assuming ideal gas behavior it is shown in Tsilingiris (2007) that

$$Gr^* = \frac{g \cdot \beta \cdot \rho_m^2 \cdot L^3 \cdot \Delta T^*}{\mu_m^2}, \quad (2)$$

where the modified temperature difference is given by the following expression

$$\Delta T^* = \Delta T + \frac{(P_{vg} - P_{vs}) \cdot (M_v - M_a) \cdot \mathrm{T_s}}{M_a \cdot P_0 + P_{vs} \cdot (M_v - M_a)}. \quad (3)$$

It has long ago been established that the convective heat transfer coefficient in an enclosed space is calculated through the average Nusselt dimensionless number from the following familiar correlation (McAdams, 1958)

$$Nu = C \cdot (Gr \cdot \mathrm{Pr})^n, \quad (4)$$

where C and n are suitable numerical constants depending on the specific region of Grashof number.

It can easily be derived that the convective heat transfer coefficient can be calculated by the following expression:

$$h_{cv} = C \cdot k_m \cdot L^{3n-1} \left(\frac{g \cdot \rho_m \cdot \beta}{\mu_m \cdot \alpha_m} \right)^n \cdot \left[(T_{\mathrm{s}} - T_{\mathrm{g}}) + \frac{T_{\mathrm{s}} \cdot (P_{vs} - P_{vg}) \cdot (M_a - M_v)}{M_a \cdot P_o - P_{vs} \cdot (M_a - M_v)} \right]^n, \quad (5)$$

where L is the characteristic length of the still, which depending on the basic still geometry and glazing configuration it is usually taken as the average distance between brine interface and the top condensing pane.

In the previous expression the thermophysical properties of the saturated mixture k_m, ρ_m, μ_m and α_m should be taken at the average still temperature. Under these conditions it can be proven (Tsilingiris, 2007), that the evaporative heat transfer coefficient is related to the convective heat transfer coefficient by the following expression:

$$h_e = 1000 \cdot h_{fg} \cdot \frac{h_{cv}}{c_{pa}} \cdot \frac{R_a}{R_v} \cdot \frac{P_o}{(P_o - P_{vs}) \cdot (P_o - P_{vg})}, \quad (6)$$

while the mass outflow of distillate which is given by the following expression:

$$\dot{m}_w = \frac{h_{cv}}{c_{pa}} \cdot \frac{R_a}{R_v} \cdot \left(\frac{P_o \cdot (P_{vs} - P_{vg})}{(P_o - P_{vs}) \cdot (P_o - P_{vg})} \right) \quad (7)$$

is directly proportional to the convective heat transfer coefficient.

Assuming that $C = 0.075$, $n = 1/3$, $M_v = 18.02$ kg/kmol, $M_a = 28.97$ kg/kmol and operational conditions corresponding to an average still temperature at 50 °C, the following saturated mixture properties can be evaluated from Tsilingiris (2007), $\rho_m = 1.04325$ kg/m^3, $k_m = 0.0269$ W/m K, $\mu_m = 1.8641 \times 10^{-5}$ Ns/m^2, $\alpha_m = 2.3929 \times 10^{-5}$ m^2/s. Under the previous assumptions and taking into account the numerical values of the involved properties, the expression (5) becomes

$$h_{cv} = 0.83502 \cdot \left[\Delta T + \frac{(P_{vs} - P_{vg}) \cdot T_s}{268 \times 10^3 - P_{vs}}\right]. \quad (8)$$

This expression is very similar to the model proposed by Dunkle (1961) and the simplified model proposed by Malik et al. (1982), except of the values of the involved numerical constants (0.884 and 268.9 in Dunkle and Malik et al., model instead of 0.83502 and 268 in the developed expression (8)) and will henceforth be referred for convenience as the simplified Dunkle's model. The difference between the values of the constant numerical multiplier in these models being higher than 5.5%, is mainly attributed to the proper consideration of humid air thermophysical properties.

Further, under the assumption that the saturated vapor pressure at brine and glass temperatures is negligible compared to the barometric pressure, the expression (6) becomes

$$\frac{h_e}{h_{cv}} = 1000 \cdot \frac{h_{fg}}{c_{pa}} \cdot \frac{R_a}{R_v} \cdot \frac{1}{P_0}. \quad (9)$$

For the following numerical values of the parameters corresponding to an average still temperature of about 50 °C, $h_{fg} = 2380$ kJ/kg, $c_{pa} = 1008$ J/kg K, $R_a = 0.287$ kJ/kg K and $R_v = 0.4615$ kJ/kg K, the ratio of the evaporative (K/Pa) to convective (W/m^2 K) heat transfer coefficients becomes independed of the operational conditions:

$$\frac{h_e}{h_{cv}} = 0.01449. \quad (10)$$

This expression is very similar to the simplified model derived by Malik et al. (1982) corresponding to a constant value of 0.013 which is about 10% lower than the one appearing in Eq. (10).

Therefore an appreciable attention should be devoted in the use of the simplified expression (10), since its accuracy degrades hopelessly at higher than about 50 °C average still temperatures. Further, although for very low still temperatures the numerical value of the multiplier $P_0/(P_0 - P_{vs}) \cdot (P_0 - P_{vg})$ in Eq. (6) becomes close to about 10^{-5} Pa^{-1} its value becomes about 20% higher at about 50 °C while it further increases very substantially at even higher temperatures.

Assuming that the evaporative heat flux in thermal equilibrium is equal to the heat of condensation, it is simply derived that

$$q_{ev} = h_e \cdot (P_{vs} - P_{vg}) = 1000 \cdot h_{fg} \cdot \dot{m}_w \quad (11)$$

from which taking into consideration the simplified expression (10) the mass outflow of the distillate yield can directly be derived by the following simplified expression:

$$\dot{m}_w = 1.2099 \times 10^{-5} \cdot \frac{P_{vs} - P_{vg}}{h_{fg}} \left[\Delta T + \frac{(P_{vs} - P_{vg}) \cdot T_s}{268 \times 10^3 - P_{vs}}\right], \quad (12)$$

where h_{fg} is the temperature depended value of the heat of vaporization for water in kJ/kg for the average still temperature.

The distillate yield, being a function of thermophysical properties, can be expressed as a function of specific heat capacity of dry air and the thermal conductivity, density, viscosity and thermal diffusivity of saturated binary mixture

$$\dot{m}_w = \dot{m}_w(c_{pa}, k_m, \rho_m, \mu_m, \alpha_m), \quad (13)$$

The distillate yield sensitivity on temperature is calculated from the following expression:

$$\frac{d\dot{m}_w}{dT} = \frac{\partial \dot{m}_w}{\partial c_{pa}} \cdot \frac{\partial c_{pa}}{\partial T} + \frac{\partial \dot{m}_w}{\partial k_m} \cdot \frac{\partial k_m}{\partial T} + \frac{\partial \dot{m}_w}{\partial \rho_m} \cdot \frac{\partial \rho_m}{\partial T} + \frac{\partial \dot{m}_w}{\partial \mu_m} \cdot \frac{\partial \mu_w}{\partial T} + \frac{\partial \dot{m}_w}{\partial \alpha_m} \cdot \frac{\partial \alpha_m}{\partial T}. \quad (14)$$

Taking into consideration the convective heat transfer coefficient from Eq. (5), it is derived from Eq. (7) that

$$\dot{m}_w = F \cdot c_{pa}^{-1} \cdot k_m \cdot \rho_m^n \cdot \mu_m^{-n} \cdot \alpha_m^{-n}, \quad (15)$$

where F is expressed as a function of the brine and condensing plate temperatures

$$F = C \cdot g^n \cdot \frac{R_a}{R_v} \cdot P_0 \cdot \left(\frac{T_s + T_g}{2}\right)^{-n} \cdot \frac{(P_{vs} - P_{vg})}{(P_0 - P_{vs}) \cdot (P_0 - P_{vg})} \cdot \left[(T_s - T_g) + \frac{T_s \cdot (P_{vs} - P_{vg}) \cdot (M_a - M_v)}{M_a \cdot P_0 - P_{vs} \cdot (M_a - M_v)}\right]^n \quad (16)$$

with C and n suitable values of numerical constants.

Assuming that $C = 0.075$ and $n = 1/3$, the following partial derivatives are calculated:

$$\frac{\partial \dot{m}_w}{\partial c_{pa}} = -F \cdot \frac{k_m \cdot \rho_m^{1/3}}{c_{pa}^2 \cdot \mu_m^{1/3} \cdot \alpha_m^{1/3}}, \quad (17)$$

$$\frac{\partial \dot{m}_w}{\partial k_m} = F \cdot \frac{\rho_m^{1/3}}{c_{pa} \cdot \mu_m^{1/3} \cdot \alpha_m^{1/3}}, \quad (18)$$

$$\frac{\partial \dot{m}_w}{\partial \rho_m} = \frac{1}{3} \cdot F \cdot \frac{k_m \cdot \rho_m^{-2/3}}{c_{pa} \cdot \mu_m^{1/3} \cdot \alpha_m^{1/3}}, \quad (19)$$

$$\frac{\partial \dot{m}_w}{\partial \mu_m} = -\frac{1}{3} \cdot F \cdot \frac{k_m \cdot \rho_m^{1/3}}{c_{pa} \cdot \mu_m^{4/3} \cdot \alpha_m^{1/3}}, \quad (20)$$

$$\frac{\partial \dot{m}_w}{\partial \alpha_m} = -\frac{1}{3} \cdot F \cdot \frac{k_m \cdot \rho_m^{1/3}}{c_{pa} \cdot \mu_m^{1/3} \cdot \alpha_m^{4/3}}. \quad (21)$$

Taking further into consideration the developed correlations in Tsilingiris (2007) which offer the thermophysical properties of the saturated mixture as a function of temperature, it is derived that

$$\frac{\partial k_m}{\partial T} = K_1 + 2K_2 \cdot t + 3K_3 t^2 \quad (22)$$

with the following values for the numerical constants: $K_1 = 5.526004579 \times 10^{-5}$, $K_2 = 4.631207189 \times 10^{-7}$, $K_3 = -9.489325324 \times 10^{-9}$

$$\frac{\partial \rho_m}{\partial T} = RO_1 + 2RO_2 \cdot t + 3RO_3 \cdot t^2 \quad (23)$$

with $RO_1 = -6.043625845 \times 10^{-3}$, $RO_2 = 4.697926602 \times 10^{-5}$, $RO_3 = -5.760867827 \times 10^{-7}$

$$\frac{\partial \mu_m}{\partial T} = MU_1 + 2MU_2 \cdot t + 3MU_3 \cdot t^2 + 4MU_4 \cdot t^3 \quad (24)$$

with $MU_1 = 9.151853945 \times 10^{-8}$, $MU_2 = -2.16276222 \times 10^{-9}$, $MU_3 = 3.413922553 \times 10^{-11}$, $MU_4 = -2.644372665 \times 10^{-13}$

$$\frac{\partial \alpha_m}{\partial T} = TD_1 + 2TD_2 \cdot t + 3TD_3 \cdot t^2 \quad (25)$$

with $TD_1 = 8.027692454 \times 10^{-8}$, $TD_2 = 1.496456991 \times 10^{-9}$, $TD_3 = -2.112432387 \times 10^{-11}$ and

$$\frac{\partial c_{pa}}{\partial T} = CA_1 + 2CA_2 \cdot (t+273) + 3CA_3 \cdot (t+273)^2 + 4CA_4 \cdot (t+273)^3 \quad (26)$$

with $CA_1 = -0.284887 \times 10^{-3}$, $CA_2 = 0.7816818 \times 10^{-6}$, $CA_3 = -0.4970786 \times 10^{-9}$ and $CA_4 = 0.1077024 \times 10^{-12}$.

The quantity $\mathrm{d}\dot{m}_w/\mathrm{d}T$ which represents the temperature sensitivity of the solar still distillate outflow owing to the temperature dependence of the involved thermophysical properties, can be calculated at any average still temperature level for the whole operational still temperature range from (14) taking into consideration the expressions (17)–(26).

3. The selection of data from experimental measurements

A massive body of published measurements reported from a substantial amount of experimental investigations both field and laboratory on the operational performance of solar stills over the last few decades is currently available from the literature. Although these measurements usually confirm theoretical predictions, they occasionally fail indicating a controversy with theoretical predictions which sometimes degrade the level of confidence in the available predictive models (Clark, 1990). However the significant amount of measured data from the broad literature could readily be employed at least for first order assessment of the earlier developed theoretical analyses and investigation of the prediction accuracy of the associated theoretical models.

Among the numerous reports on laboratory and field measurements, efforts have been made to select data from relatively recent and mostly reliable literature sources presenting representative measurements preferably in tabular form, from devices of clearly defined geometry and dimensions. When the results are available in the form of plotted graphs, numerical data are derived from the graphical compilation of scanned plots. Between various earlier publications in the literature, the following most representative reports were selected and will be briefly presented and discussed in the present section in chronological order.

In an attempt to evaluate the predictive accuracy of the convective heat transfer coefficient as derived from correlations which were earlier recommended in the literature, Adhikari et al. (1990) has carried out laboratory mass transport measurements using a experimental device composed of a square horizontal condensation and an electrically heated evaporation metal tray using hot plate heaters underneath. These mostly high temperature measurements are available in the form of tabular data and correspond to a broad range of average temperatures and temperature differences ranging between about 19–84 °C and 12–30 °C, respectively, with maximum evaporation tray temperatures as high as 92 °C.

Shawaqfeh and Farid (1995) have also carried out indoor and outdoor measurements in a still with a single condensing glass pane 92 °C. For the purpose of the present investigation experimental data were derived from the graphical compilation of plotted field measurements reported from a passive single slope solar still with an inclination angle of 19 deg., covering an average solar still temperature range from about 26 to 60 °C, with typical temperature differences between brine and condensing plate ranging between about 5 and 9 °C.

Kumar and Tiwari (1996) have carried out field measurements in active and passive stills with a top glass pane inclination of 15 deg., aiming to gather sufficient experimental data for the precise evaluation of specific constants in the convective heat transfer correlation based on regression analysis. The selected measurements which were presented in tabular data form correspond to passive stills operating at average still temperatures ranging between about 38 and 52 °C, with temperature differences ranging typically from about 4 to 8 °C.

Aiming to investigate the effects of condensing plate inclination angle and cavity volume on the convective heat transfer correlation, Tiwari et al. (1997) also carried out measurements in a laboratory still with a condensing plate inclination of 7.3 and 14.3 deg. in a carefully controlled laboratory environment, using thermostatic control of brine and condensing pane temperatures. The measurements were carried out at three specific average still temperature levels of about 28, 55 and 73 °C, with rather unusually high temperature differences of about 36, 17 and 20 °C, respectively.

Further field investigations have been carried out by Aggrawal and Tiwari (1998), covering a wide temperature range, aiming to investigate the influence of a broadly varying average still temperature on the convective heat transfer in the still enclosure. The reported measurements in the form of tabular data were derived from an experimental single slope solar still of conventional design with a spacing between brine surface and condensing plate of about 15 cm. These measurements correspond to an average still temperature, ranging between about 23 and 75 °C and to temperature differences ranging from about 2 to 12 °C.

A vast amount of field measurements were also derived by a carefully monitored double slope experimental solar still as reported by Voropoulos et al. (2000). Although the derived data from this investigation were compiled from plotted results corresponding to medium and low average still temperatures ranging from about 36 °C down to 7 °C with temperature differences between about 3 and 15 °C, their particular significance is associated to the rather unusual solar still geometry. Its predominant design characteristic is related to the very large solar still dimensions and the substantial cavity volume (2.12×5.0 m $= 10.6$ m^2 surface area with about 1 m height), as well as to the large sloping angles (60 deg and 30 deg.) of the top condensing glazing.

Experimental data from a single-tray laboratory still have also recently been reported by Hongfei et al. (2002), aiming to derive convective heat transfer correlations for the specific still design of a relatively small cavity volume corresponding to about 0.06 m brine and condensing plate spacing. These medium and high temperature measurements which are available in tabular form, correspond to an average still temperature and a temperature difference ranging between about 37–80 °C, and 6.5–15.5 °C, respectively, with a maximum brine temperature as high as 85.5 °C.

4. Results and discussion

From the gathered measurements, corresponding distillate yield data in the form of mass outflow per unit time and solar still basin area were derived, which comprised a considerable body of experimental data, suitable for comparisons with predictions according to the theory. Towards this aim, the predicted distillate outflow yield was first calculated from Eq. (12) according to the simplified Dunkle's model, based on the corresponding brine and condensing plate temperatures. Additional results were also derived according to the refined model from the expression (7), based on the calculation of the convective heat transfer coefficient as derived from the expression (5) for $C = 0.075$ and $n = 1/3$ and taking explicitly into account the temperature dependence of saturated mixture thermophysical properties from recently published correlations in Tsilingiris (2007). All numerical calculations have been carried out in a conventional microcomputer through specifically developed codes programmed in BASIC.

4.1. Comparative presentation of measurements and predictions

Aiming to compare the derived measurements with theoretical predictions, the measured data from the various experimental investigations were plotted against corresponding data derived from theoretical calculations according to the simplified Dunkle's model in Fig. 1. The same data were also plotted against predictions according to the improved accuracy refined model in Fig. 2.

As derived from the inspection of these plots, although the available data cover a wide range of distillate yield measurements varying within about three orders of magnitude, they are mostly spread closely to the unity slope diagonal line, indicating a sufficiently good agreement between predictions and measurements over the whole range of distillate yield, between about 0.002 and 2 gr/m^2 s. However it is shown from the distribution of data points, the majority of measurements from these investigations correspond to a more confined mass flow rate range between 0.01 and 0.2 gr/m^2 s. Most of these data are lying almost on the unity slope diagonal line, indicating an impressively good agreement between measurements and predictions at this particular yield range, except of a few data by Aggrawal and Tiwari (1998) as well as Shawaqfeh and Farid (1995), which deviate suggesting higher predictions than measurements from both models.

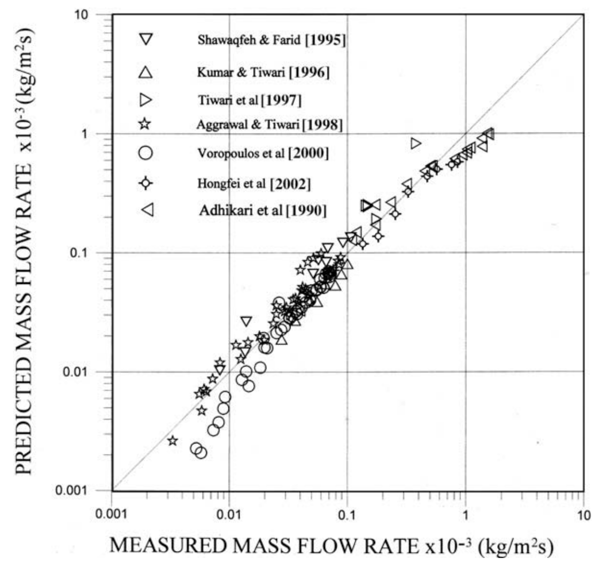

Fig. 1. Outflow distillate mass flow rate data as measured from various investigations, plotted against corresponding theoretical predictions according to the simplified fundamental Duncle's model.

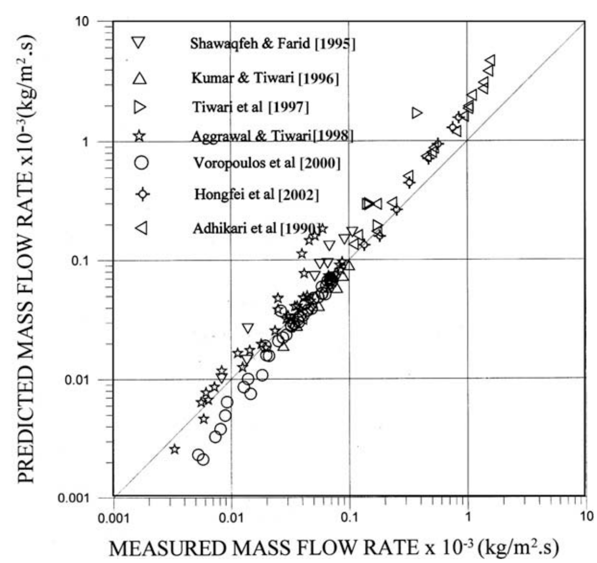

Fig. 2. Outflow distillate mass flow rate data as measured from various investigations, plotted against corresponding theoretical predictions according to the developed improved accuracy refined model.

Regarding the theoretical predictions from the simplified Dunkle's and the refined theoretical model and as derived from a comparable inspection between these figures, it is shown that although there is a very close agreement between results from both models at the low and medium temperatures, the deviation between predictions grows markedly at higher operational temperatures as typically indicated by Adhikari et al. (1990) as well as by Hongfei et al. (2002) data.

A more noticeable scattering and pronounced deviation between results from the two predictive models is indicated at mass flow rate of distillate yield, typically higher than 0.2 gr/m^2 s, corresponding usually to operation at higher temperature levels. This is obviously attributed to the effect of relaxing the assumption that the saturated vapor pressure is negligible as compared to the barometric pressure in the simplified Dunkle's model, something which shifts the high temperature data derived by the refined model upwards. This is typically shown by the deviations between predictions from the two models, corresponding mainly to the most of Adhikari et al. (1990) high temperature and yield data in addition to the four higher yield Hongfei et al. (2002) as well as Aggrawal and Tiwari (1998) data points, showing that at the corresponding higher operational temperatures more conservative predictions were derived by the simplified Dunkle's model.

Although these data by Hongfei et al. (2002) and Aggrawal and Tiwari (1998) are spread over about the same temperature range corresponding to about 72–79 °C and 72–75 °C, respectively, they are lying at a region of a different distillate yield range, something which is attributed to the appreciably lower measured temperature differences in the case of Aggrawal and Tiwari (1998) data. These are typically of 4 °C as compared to Hongfei et al. (2002) data which are close to 15 °C. The same occurs for the similar reason in the case of the high temperature data point corresponding to an average and a brine temperature of about 73 and 83 °C, respectively from Tiwari et al. (1997) corresponding to 0.383 gr/m^2 s and to a lesser degree in a few higher temperature Shawaqfeh and Farid (1995) data. For the medium average temperature level measurements by Aggrawal and Tiwari (1998), Shawaqfeh and Farid (1995), Kumar and Tiwari (1996) as well as Adhikari et al. (1990) and for the medium and low temperature data by Voropoulos et al. (2000), there is a very good agreement between results from both models.

Referring to the level of agreement between theoretical results and measurements, it is derived from the distribution of the plotted data in Figs. 1 and 2 that generally there is a sufficiently good agreement between results for the majority of data points corresponding to the medium temperature range, which represent the usual operational conditions in practical solar stills. However for conditions corresponding to higher than about 65 °C temperatures and about 0.1 gr/m^2 s mass flow rates, represented mainly from Adhikari et al. (1990), Hongfei et al. (2002), Aggrawal and Tiwari (1998) as well as from Tiwari et al. (1997) data, Dunkle's simplified model tends to under predict measurements while there is a trend for over prediction according to the proposed refined model, with deviations growing as the operational temperature increases.

Regarding the measurements by Tiwari et al. (1997), it should be mentioned that although they have been carried out in a carefully controlled laboratory environment, at three distinct low, medium and high average temperature levels corresponding to about 28, 55 and 73 °C, respectively, there is a close agreement between predictions and measurements at the low and medium average temperature levels, while again predictions are overestimated at high operational temperatures.

Referring to the field measurements from Voropoulos et al. (2000), it should be pointed out that although they were derived from a solar still of an unusually large cavity, operating at low average temperatures corresponding to a low outflow yield ranging between 0.01 and 0.1 gr/m^2 s, they are lying closely to the unity slope line, indicating a good agreement with theoretical predictions. However as the measured yield decreases at very low levels, typically lower than 0.01 gr/m^2 s corresponding to unusually low operational temperatures, theoretical predictions from both models tend to underestimate measurements. This may be attributed to various reasons among which are the increasing outflow measurement errors and uncertainty at very low yield levels as was also noted for example in Kumar and Tiwari (1996) and the unusually low average and top condensing plate temperatures, as low as 7 and 4 °C, respectively, where the accuracy of the employed transport property correlation fits may also become marginal.

4.2. The influence of thermophysical properties

Since the working medium in solar stills is a binary mixture of water vapor and dry air, its thermophysical and transport properties should explicitly be taken into account in the calculations. Although the lack of access on proper readily available humid air properties has occasionally in the past made necessary the use of corresponding dry air data, humid air property values being strong functions of temperature and molar fraction of water vapor are completely different than those of dry air.

Recent calculations based on first order linear mixing considerations (Tsilingiris, 2007) have allowed the evaluation of the pertinent thermophysical properties of humid air as a function of temperature and relative humidity for relevant heat and mass transport calculations. Further investigations have recently allowed the calculation of the full range of thermophysical and transport properties of humid air based on more accurate molecular theory considerations and comparisons with a few existing measurements from the literature (Tsilingiris, 2008). Comparison between results from these investigations and few available earlier laboratory measurements indicates an impressively good agreement and confirms the adequate accuracy level of results. Comparisons between derived humid air properties from both investigations indicates a very good agreement between humid air data according to simple linear mixing and refined molecular considerations for the purpose of first order investigations and engineering calculations of ordinary accuracy level. Assuming that the working medium is close to saturation conditions, the pertinent thermophysical properties involved in the relevant heat and mass transport processes in solar stills for the purpose of the present investigation were simply derived by the previously published algebraic correlations of temperature in Tsilingiris (2007).

The quantity $d\dot{m}_w/dT$ representing the temperature sensitivity of the solar still distillate outflow owing to the temperature dependence of thermophysical properties was calculated as a function of average still temperature in 1 °C temperature intervals for the whole temperature range of applications and a fixed temperature difference $\Delta T = T_s - T_g$. The derived results which are shown in Figs. 3–5 correspond to temperature differences of 10, 20 and 30 °C, respectively. The contribution of each additive term in Eq. (14) corresponding to each specific thermophysical property is shown with broken lines in the plots 3, 4 and 5, while the corresponding combined overall effect on distillate output sensitivity is indicated by the thick solid line.

The comparative combined effect of thermophysical properties on the value of $d\dot{m}_w/dT$ is shown in Fig. 6 for the three selected values of temperature difference of 10, 20 and 30 °C. It can be seen from these plots that although the specific effect of each individual property involved into calculations may be significant, the overall contribution is relatively small and of negative sign, owing to the canceling out effect of individual contributions. It can also be seen that although this effect becomes for a $\Delta T = 10$ °C practically noticeable at considerably high average still temperatures, typically higher than about 70 °C, for higher temperature differences up to $\Delta T = 30$ °C it becomes significant at far lower temperatures as low as 50 °C.

This supports the rather weak dependence of the derived mass flow rate on the temperature dependent saturated mixture properties at ordinary operating temperatures and explains their moderate effect at higher average temperatures although the temperature dependence of specific saturated mixture properties may be significant.

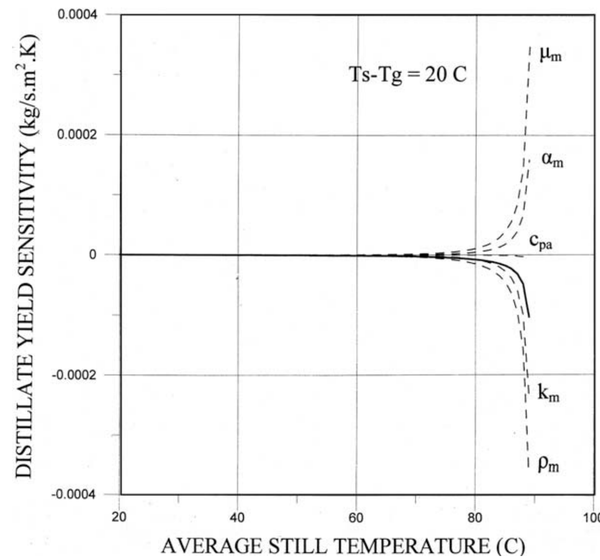

Fig. 4. Temperature sensitivity of outflow yield $d\dot{m}_w/dT$, (solid line) as derived from the temperature dependence of the pertinent thermophysical properties of wet saturated air (broken lines) at various average still temperature for $\Delta T = T_s - T_g = 20$ °C.

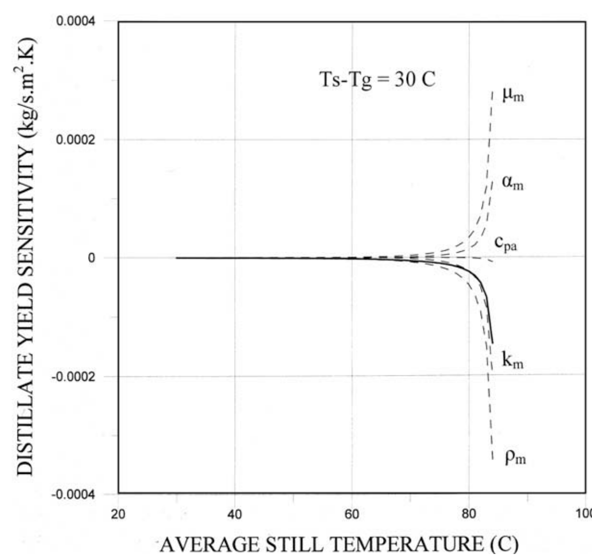

Fig. 5. Temperature sensitivity of outflow yield $d\dot{m}_w/dT$, (solid line) as derived from the temperature dependence of the pertinent thermophysical properties of wet saturated air (broken lines) at various average still temperature for $\Delta T = T_s - T_g = 30$ °C.

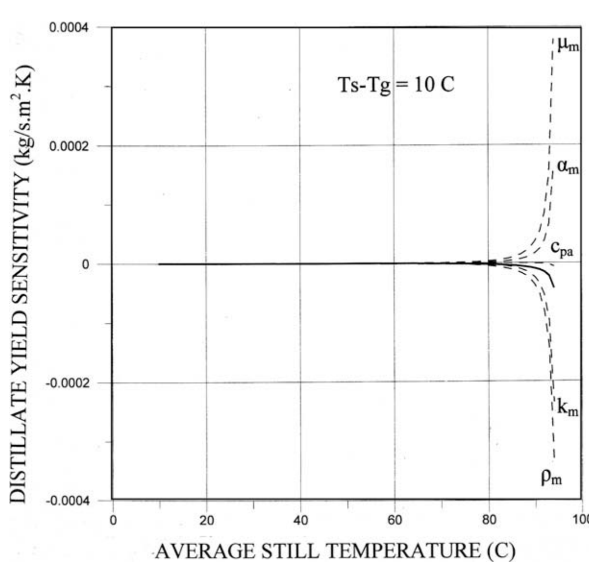

Fig. 3. Temperature sensitivity of outflow yield $d\dot{m}_w/dT$, (solid line) as derived from the temperature dependence of the pertinent thermophysical properties of wet saturated air (broken lines) at various average still temperature for $\Delta T = T_s - T_g = 10$ °C.

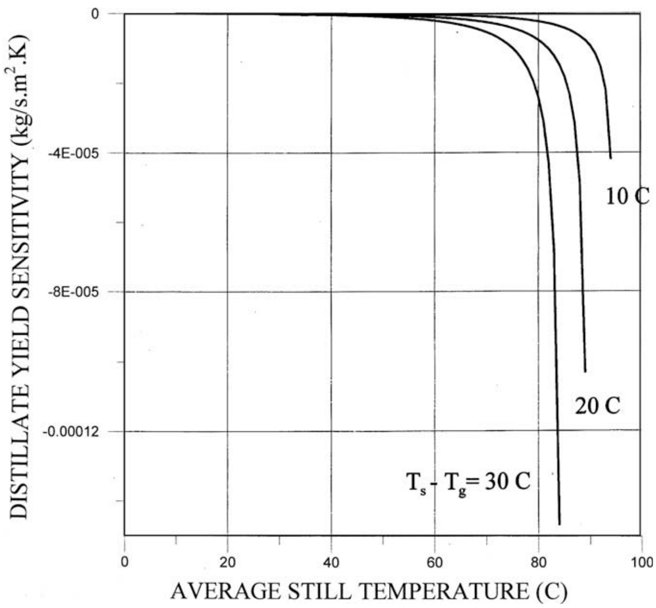

Fig. 6. The comparative temperature sensitivity of outflow yield $d\dot{m}_w/dT$ at various average still temperature for $\Delta T = T_s - T_g = 10$ °C, 20 °C and 30 °C.

Therefore it appears that the relatively high deviations between predictions and measurements for specific high temperature data as shown in Figs. 1 and 2, is rather irrelevant to the effect of thermophysical properties, something which is also confirmed by the satisfactory predictive accuracy of both predictive models, at least as far as the lower operational temperatures is concerned.

4.3. The effect of convective heat transfer correlations

The model representing the convective heat transfer within the confined space of a passive solar still is approximately that of a horizontal enclosure, filled with a fluid heated from below. The issue of fundamental importance in such systems is that the imposed temperature differential between the bounding horizontal surfaces should exceed a critical value before convective motion is detected. In the case of enclosures with sufficiently wide horizontal dimensions as compared to their spacing distance, the onset of convection according to the theory occurs at a critical Ra number higher than $Ra \geqslant 1708$ when cellular motion begins, known as Bernard convection. This motion becomes considerably more complicated as Ra increases, while at several orders of magnitude higher than critical value as usually occurs in solar stills, the motion becomes oscillatory and turbulent.

The problem has attracted considerable attention by various, earlier and more recent investigators. Jakob et al. (1949), having correlated extensive earlier derived data for air by Mull and Reiher (1930), reported a Nusselt–Rayleigh number correlation for air in the familiar form of expression (4) and recommended that $C = 0.21$ and $n = 1/4$ for $3.2 \times 10^5 > Gr > 10^4$, while $C = 0.075$ and $n = 1/3$ for $10^7 > Gr > 3.2 \times 10^5$.

Following further experimental work by Globe and Dropkin (1959) the following correlation has been recommended:

$$Nu = C \cdot Ra^n \cdot \mathrm{Pr}^m, \tag{27}$$

valid in the range of $7 \times 10^9 > Ra > 3 \times 10^5$ with $C = 0.069$ and $n = 1/3$, which is very similar to Eq. (4) since the recommended value for $m = 0.074$. Substantial experimental evidence supports that although the exponent of the expression is close to $n = 0.29$ at very low Ra, it becomes practically $n = 1/3$ for higher Ra values relevant to solar still operation. Hollands et al. (1975, 1984, 1976) after having reviewed the past literature on the asymptotic behavior of the Nu number as Ra approaches infinity, confirmed the $n = 1/3$ dependence for strongly turbulent convective flow which persists as Ra increases at considerably high values, and carried out measurements on convection in layers at any inclination angles, using various fluids and covering a wide range of Prandtl numbers. The outcome of this investigation was the development of a Nusselt–Rayleigh correlation which is very similar to Eq. (4) although with $C = 0.0557$ and $n = 1/3$. This correlation is valid for conditions of turbulence and covers various fluids corresponding to a wide range of Prandtl numbers, including the saturated dry air and water vapor mixture at the highest operating temperatures which as derived in Tsilingiris (2008) corresponds approximately to $Pr = 1$.

According to the theory which is strongly supported by extensive experimental evidence, although slightly lower exponent values may be expected at appreciably lower Ra numbers which correspond to conditions not relevant to solar still operation, there is an adequately strong confidence on the value of $n = 1/3$ at large Ra numbers corresponding to practical still operation.

However, it is not certain that the value of the constant multiplier as recommended by Jacob $C = 0.075$ may be valid for the entire operational range of solar stills, something which may be supported for example by the lower reported values in the literature by Globe and Dropkin (1959) ($C = 0.069$) and which may very possibly support the sporadically appearing controversial predictions and measurements at higher operational temperatures (Clark, 1990).

Since it is probable that the inclination angle of the top condensing plate is likely is going to affect the flow conditions in the still enclosure as also noted in Rheinlander (1982), Tiwari and Lawrence (1991) have recommended the use of an inclination depended correlation, developed by Hollands specifically for air and for $0 < \beta < 75$ deg. However, for Rayleigh numbers few orders of magnitude higher than critical and typically for $Ra > 10^6$ as it usually occurs in the solar stills of ordinary design, this correlation simplifies into the familiar form $Nu = C \cdot Ra^n$ with $n = 1/3$ and C a function of the inclination angle β, so as

$$\frac{Nu(\beta)}{Nu(\beta = 0)} \cong (\cos\beta)^{1/3} = \xi. \tag{28}$$

Since in most solar still designs it happens that $\beta \leqslant 20$ deg., it can be derived that for inclination angles up to about $\beta = 20$ deg., the numerical value of the ratio ξ in the expression (28) becomes $\xi = 0.979$ which is very close to unity. For unusually high inclination angles, as high as $\beta = 60$ deg., the same ratio becomes $\xi = 0.794$. This practically suggests a very slight dependence of the average Nusselt number on the inclination angle, at least as far as the ordinary still design is concerned corresponding to practical inclination angles as high as $\beta = 20$ deg., corresponding to lower than about 2.2% deviation from the horizontal layer Nusselt number value. This deviation increases at values as high as 21% for extremely high inclination angles corresponding to about $\beta = 60$ deg., something which still cannot explain the sporadically appearing deviations between theoretical predictions and measurements.

Substantial attention has been devoted by various earlier investigations (Adhikari et al., 1990; Kumar and Tiwari, 1996; Aggrawal and Tiwari, 1998) to derive improved accuracy values of the numerical constant C and exponent n in the dimensionless convective heat transfer correlation, based on regression analysis of experimentally derived data. Aiming to calibrate the theory using the data base of gathered experimental measurements, a different approach was followed for the development of an approximate convective heat transfer correlation. This was based on the adequate confidence of the $n = 1/3$ dependence in the Nusselt number correlation for the flow in the fully turbulent flow regime, which has led to the first order estimation of the numerical constant C based on the available massive body of data from individual measurements. Towards this aim the convective heat transfer coefficient was calculated, based on the measured value of distillate

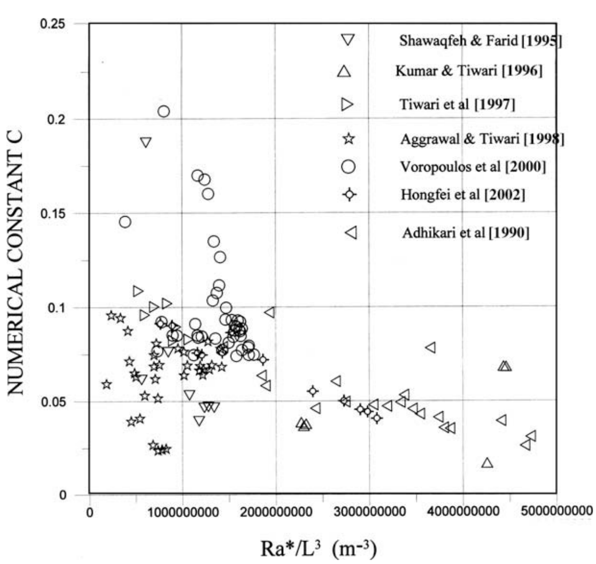

Fig. 7. The calculated numerical constant C as derived from the experimental measurements derived from various investigations, corresponding to different data points as a function of the dimensional ratio (Ra^*/L^3) ranging between 0 to 5×10^9.

yield outflow and the pair of temperatures T_s and T_g from the expression (7). This was employed for the evaluation of the numerical constant C from the expression (5), taking into account the temperature depended properties of specific heat capacity of air and density, viscosity, thermal conductivity and thermal diffusivity of saturated mixture from the correlations as derived in Tsilingiris (2007) and a fixed value of $n = 1/3$.

The results showing the distribution of the numerical value of the constant C in the whole range of the modified dimensional number (Ra^*/L^3) is shown in Fig. 7.

It was found necessary to avoid the reference of available measurements to the common dimensionless Rayleigh number since it is proportional to the cube of the characteristic length L, which is not uniform to all measurements. Therefore, the dimensional rather than the dimensionless Rayleigh number were employed to avoid misinterpretation errors in the distribution of data points in Fig. 7. This could be very probable as L cannot accurately be defined for each particular experimental still of a completely different cavity geometry and design during the course of the measurements, although for a typical characteristic length of about $L = 0.15$ m which is definitely not representative of all measurements, most of the data refer to sufficiently high dimensionless Rayleigh numbers corresponding to conditions of strong turbulence.

The dimensional parameter was also selected since it is interesting to note that it is related as shown below, to the ratio of the two significant operational parameters ΔT^* and $\overline{T}$ which strongly influence the solar still performance

$$\frac{Ra^*}{L^3} = \frac{g}{\nu_m \cdot \alpha_m} \cdot \frac{\Delta T^*}{\overline{T}}. \tag{29}$$

It is indicated from Fig. 7 that for the lower dimensional Ra numbers, typically lower than 2×10^9 m^{-3}, the majority of measurements are spread between 0.07 and 0.08 suggesting an increased confidence on a Nusselt number correlation form similar to Eq. (4). Few data which were either derived during operation at unusually low average temperatures ranging typically between about 6 and 10 °C corresponding to very low distillate yields as reported from Voropoulos et al. (2000) or at conditions corresponding to higher than 70 °C average temperatures as reported from Aggrawal and Tiwari (1998), scatter appreciably within the same dimensional Rayleigh parameter range. However it is clear that the numerical value of constant tends to decrease at the neighbourhood of 0.05 at higher Rayleigh dimensional parameters.

Although the outflow distillate yield is strongly influenced by both the operational parameters ΔT^* and $\overline{T}$, it appears that their ratio lacks in clear physical significance, since the distillate yield being a directly measured quantity is proportional to both these parameters.

In Fig. 8 the derived results were plotted against the outflow mass flow rate, ranging between about 2×10^{-3} and 2 gr/m^2 s. The distribution of data points in this plot indi-

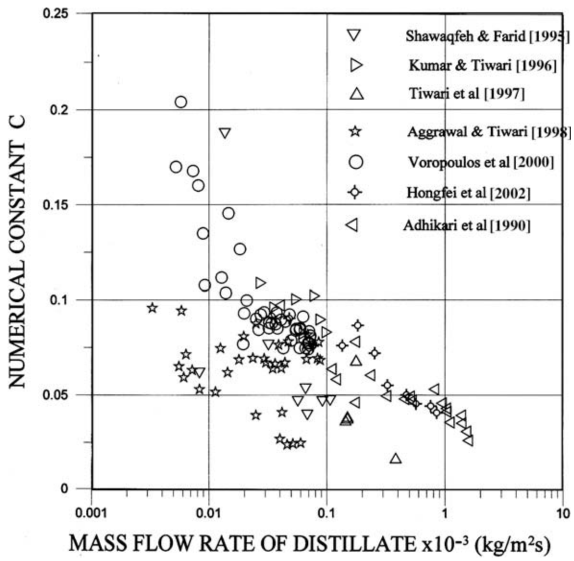

Fig. 8. The calculated numerical constant C as derived from the experimental measurements derived from various investigations corresponding to different data points as a function of the outflow rate of distillate.

cates a clear trend of reduction of the numerical constant C, as the distillate yield increases within almost three orders of magnitude. More specifically, although its value is around 0.075 for typical distillate yields of ordinary solar stills between 0.01 and 0.1 gr/m^2 s, it markedly decreases at higher than 0.1 gr/m^2 s yields, which mainly correspond to the high temperature range of solar still operation.

This clearly indicates that although the Nusselt number correlation (4) with a proportionality constant close to $C = 0.075$ may be accurate for the conditions of turbulence in the solar still enclosure at lower than typically 0.1 gr/m^2 s, it fails to model with appropriate accuracy the conditions occurring at higher yields corresponding to higher operational temperatures, where a lower value around 0.05 should be selected.

5. Conclusions

A substantial amount of combined theoretical and experimental investigations have already been carried out towards better understanding of the interrelated heat and mass transport mechanisms in solar stills, which has contributed to acquiring an adequate level of confidence on the existing background theory, at least as far as ordinary conditions of operation are concerned. However, owing to the controversies between theoretical predictions and measurements which appear sporadically in the literature, there is an ongoing dispute about the accuracy level and an ongoing discussion about the validity of the predictive theories, as applied at the entire range of operating conditions, proving that our knowledge on transport processes is still far from being complete.

Based on a comprehensible review of the relatively recent literature and aiming to exploit past published experimental investigations which were carried out under a wide range of operational conditions, a data base of measurements was developed aiming to evaluate the validity of the broadly established fundamental Dunkle's theoretical model, as well as its more refined version derived by the relaxation of several simplified assumptions.

It is impressive that irrespectively of weather the selected measurements were laboratory or field, having been carried out in stills of a different design and geometry, at different times, in various laboratories with equipment of different technology level and facilities, under completely different specific conditions which may even be not completely known, they have been found to be consistent with the theory.

More specifically although at least as far as the usual range of distillate yield up to about 0.1 gr/m^2 s is concerned, the predictive accuracy is impressively good for both models, for higher yields and operational temperatures it markedly degrades. Based on these measurements it has been found that the prediction accuracy of the developed refined model can considerably be improved for strongly turbulent flow conditions in the still enclosure corresponding to high operation temperatures, simply by the appropriate correction of the numerical constant in the Nusselt–Rayleigh correlation, at a value around or slightly lower than 0.05. It is clear however that more conclusive measurements are required for the accurate evaluation of the appropriate form of the convective heat transfer correlation for higher operational temperatures, where the influence of thermophysical properties becomes noticeable and the saturation vapour pressure at the brine and condensing plate and the effect of transport properties are appreciably strong.

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