Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 14 (23): 3344-3348, 2014
ISSN 1812-5654 / DOI: 10.3923/jas.2014.3344.3348

Heat Transfer Energy Balance Model of Single Slope Solar Still

Kiam Beng Yeo, Cheah Meng Ong and Kenneth Tze Kin Teo
Materials and Minerals Research Unit, Faculty of Engineering, Universiti Malaysia Sabah,
Jalan UMS, Kota Kinabalu, 88400, Sabah, Malaysia

Abstract: Single slope solar still absorbs the thermal energy from sunlight to distillate polluted water into clean water in an enclosed space. Principal of heat transfer and energy balance were the governing equations for the operation of single slope solar still. A mathematical model was developed to express these thermodynamics behaviours. In the model, critical parameters had been identified, such as slope angle of glass cover, mass of water in basin and wind speed. Simulation had been carried out and results revealed the importance of the slope angle matching the latitude of the experimental location, the increasing of water mass in the basin leading to decreasing of clean water production and the presence of wind speed also increase the output only when the sunlight is still sufficient.

Key words: Solar still, heat transfer, energy balance, evaporation

INTRODUCTION

Water treatment process utilizing the solar distillation technology enables human beings to acquire clean water supply with the simplest and economical way possible. To ensure consistent quality and productivity, single slope solar still has undergone numerous studies to eventually evolve into a simple design and functionality, portability and low maintenance (Abdallah and Badran, 2008). It consists of a basin, covered by a transparent cover with certain slope angle and a drain to collect and redirect the condensate water vapour into a container (Kumar and Tiwari, 2009). Solar still being first used in 1872 in a mining community at the northern deserts of Chile, which saved 33% of the cost compared to transporting water from 100 km distance away (Howe, 1986; Ismail, 2009).

Mathematical model has been very useful in predicting the performance of single slope solar still at different locations and climate throughout the whole year. Dunkle (1961) has been attributed as the first to propose the complete heat and mass transfer correlations of single slope solar still. Since then, various researchers has experimented the Dunkle's model. For example, Dwivedi and Tiwari (2009) concluded that Dunkle model has been able to predict well for solar stills only with low basin water depth (0.01-0.03 m). Other authors like Hongfei *et al.* (2002) has also claimed to develop their own model that outperforms the Dunkle's model under certain operating conditions.

Computational Fluid Dynamics (CFD) software and MATLAB are other analytical tools and techniques that can further elaborate the mathematical model (Panchal and Shah, 2011; Setoodeh *et al.*, 2011; Akash *et al.*, 2000). This study presented the heat transfer energy balance model of a single slope solar still taking into account the critical parameters and conditions. The influences of these parameters to the performance of solar still are also discussed in the simulation result.

GOVERNING EQUATION

The productivity of a single slope solar still is highly dependent on the evaporation rate of water and the condensation rate of water vapour in it. The heat transfer energy balance model is therefore presented and predicted based on some of the critical parameters such as solar irradiance, glass cover angle, system temperatures, heat transfer coefficient and effective absorptivity and transmissivity. Figure 1 illustrates various energy quantities in the single slope solar still model.

To begin with, assumptions has been made in the model, such that the level of water in the basin is at a constant level, no vapour leakage in the still takes place, and the heat capacity of absorbing material, insulation and glass cover are negligible. Thus, the heat transfer energy balance in and out of the solar still is performed considering the three main components; basin, water in the basin and glass cover.

Basin is described as following Eq. 1:

$$A_b a_b G = A_b(q_{tb}+q_{loss}) \quad (1)$$

Corresponding Author: Kiam Beng Yeo, Materials and Minerals Research Unit, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, Kota Kinabalu, 88400, Sabah, Malaysia

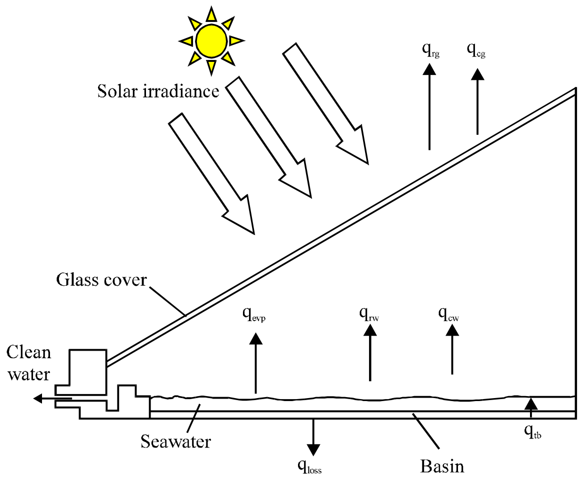

Fig. 1: Various energy quantities in single slope solar still

Water in the basin is described as following Eq. 2:

$$A_w a_w G + A_b q_{tb} = (MC)_w \frac{dT_w}{dt} + A_w (q_{rw} + q_{cw} + q_{evp}) \quad (2)$$

Glass cover is described as following Eq. 3:

$$A_g a_g G + A_w (q_{rw} + q_{cw} + q_{evp}) = A_g (q_{rg} + q_{cg}) \quad (3)$$

Glass cover heat transfer coefficient: The relationship between the surface area of glass cover, surface area of water in the basin and area of basin can be shown as in the Eq. 4 and 5:

$$A_w = A_b \quad (4)$$

$$A_g = A_b \sec\theta \quad (5)$$

The heat transfer rates for the glass cover mentioned in Eq. 3 can be further elaborated by introducing the overall glass cover heat transfer rate, q_{tg} as shown in the Eq. 6:

$$q_{tg} = q_{rg} + q_{cg} = (h_{rg} + h_{cg})(T_g - T_a) \quad (6)$$

Basin heat transfer coefficient: Heat is initially transferred from the basin to water in basin and then eventually to the glass cover. At the same time, there will be heat losses from the basin to the surrounding as well as mentioned in Eq. 7 and 8:

$$q_{tb} = h_{tb}(T_b - T_w) \quad (7)$$

$$q_{loss} = h_{loss}(T_b - T_a) \quad (8)$$

Water heat transfer coefficient: Radiation, convection and evaporation process happened when heat is transferred from water to the glass cover. The total water heat transfer coefficient and the respective heat transfer coefficients are introduced as mentioned in Eq. 9: (Dunkle, 1961; Cooper, 1973):

$$q_{tw} = (h_{rw} + h_{cw} + h_{evp})(T_w - T_g) = h_{tw}(T_w - T_g) \quad (9)$$

Overall heat transfer equation: All the heat transfer rates defined are then substituted into the equations Eq. 1, 2 and 3, respectively. By restructuring and solving these three equations with initial condition when t = 0 s, $T_w = T_{w0}$ and $T_g = T_{g0}$, the water temperature (T_w), glass cover temperature (T_g) and basin temperature (T_b) can be written as:

$$T_g = \frac{a_g G \sec\theta + h_{tg} T_a \sec\theta + h_{tw} T_w}{h_{tg} \sec\theta + h_{tw}} \quad (10)$$

$$T_b = \frac{a_b G + h_{tb} T_w + h_{loss} T_a}{(h_{tb} + h_{loss})} \quad (11)$$

$$T_w = \frac{A_b (a_{eff} G + (U_b + U_t) T_a)}{z (MC)_w} \left[1 - \frac{\exp(-zt)}{z}\right] + \frac{\exp(-zt)}{z} T_{w0} \quad (12)$$

Where:

$$a_{eff} = a_w + a_b \left(\frac{h_{tb}}{h_{tb} + h_{loss}}\right) + a_g \left(\frac{h_{tw} \sec\theta}{h_{tg} \sec\theta + h_{tw}}\right) \quad (13)$$

$$U_b = \frac{h_{tb} h_{loss}}{h_{tb} + h_{loss}} \quad (14)$$

$$U_t = \frac{h_{tw} h_{tg} \sec\theta}{h_{tg} \sec\theta + h_{tw}} \quad (15)$$

$$z = \frac{A_b (U_b + U_t)}{(MC)_w} \quad (16)$$

From the above, with evaporative heat transfer coefficient (h_{evp}) determined, the mass flow rate of water evaporated can also be determined using the Eq. 17:

$$\dot{m} = \frac{h_{evp}}{h_{fg}} (T_w - T_g) \quad (17)$$

RESULTS

The heat transfer energy balance model derived is simulated using the MATLAB solver with the known

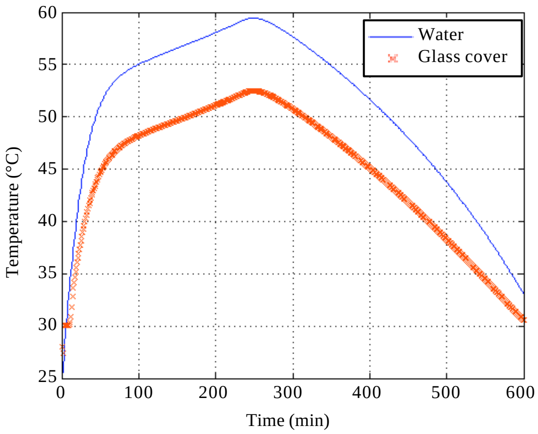

Fig. 2: Basin water temperature and glass cover temperature vs. time graph

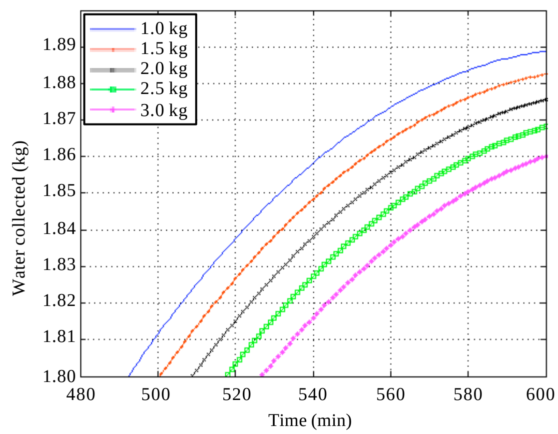

Fig. 4: Effect of water mass in basin to the mass flow rate

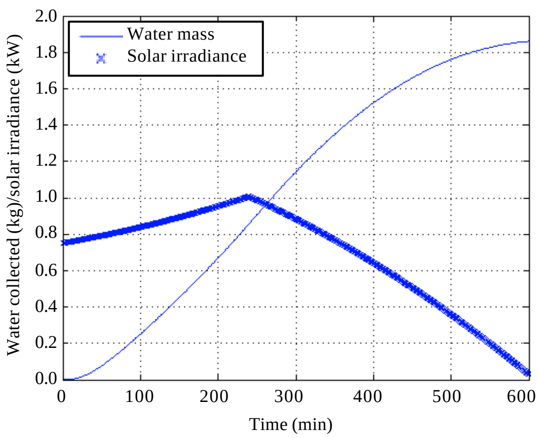

Fig. 3: Water mass collected and solar irradiance vs. time graph

Table 1: Parameters defined for simulation purpose

Parameters	Values
Initial water temperature (T_{w0})	25°C
Initial glass cover temperature (T_{g0})	28°C
Initial ambient temperature (T_a)	30°C
Basin absorptance (a_b)	0.5
Glass cover absorptance (a_g)	0.05
Water absorptance (a_w)	0.01
Glass cover emissitivity (E_g)	0.84
Water mass (M_w)	3 kg
Wind speed (V)	0 m sec^{-1}
Total simulation time	600 min

surrounding parameters defined in Table 1. Figure 2 showed the trend of clean water amount collected and solar irradiance versus time while, Fig. 3 showed the behaviour of the glass cover temperature and water temperature in the basin throughout the time. With basin area of 1 m^2 and slope angle of 10° facing true South, a total amount of about 2 kg of clean water is predicted.

The temperature difference between water and glass cover temperature indirectly reflects on how fast the heat can escape through the glass cover; the low absorbance and thin glass cover contributed to fast condensation of water vapour. In a single day, the intensity of solar irradiance varies and the slope angle of glass cover also affects the amount of sunlight reaching the basin. Zero reflection can only happen if the slope angle is exactly the same as the angle of incidence of the sunlight. Thus, the optimum slope angle should be the same as the experimental location's latitude angle so that maximum zero reflection sunlight can be obtained.

The basin in the single slope solar still can contain different mass of water at one time, depending on the design. This amount of water mass M_w will directly affect how fast the water temperature T_w will rise with response to the amount of sunlight received. According to the Fig. 4, the mass flow rate decreased as the mass of water in the basin increased, which is logical as more time is required to achieve the same temperature increase for the same amount of heat energy received from the sunlight.

Wind speed (V) is also one of the factors which affects the output of a single slope solar still. Increasing wind speed will lead to increase in the glass cover convective heat transfer coefficient (h_{cg}) which is supposed to allow heat to escape through the glass cover more efficiently. However, from the Fig. 5 and 6, the claim is only true for the first 200 min of simulation as the output of solar still begins to decrease with increasing wind speed after that. This behaviour can be explained, as the solar irradiance begins to decrease around 230th min, wind will hasten the drop of the temperature inside the solar still and eventually caused the decrease of the evaporation rate of the water in basin.

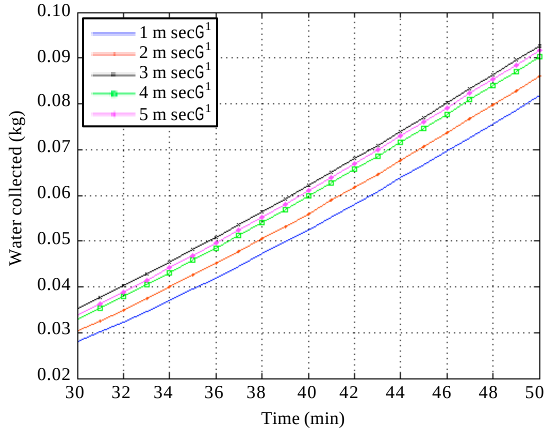

Fig. 5: Effect of wind speed to the mass flow rate at early stage of simulation

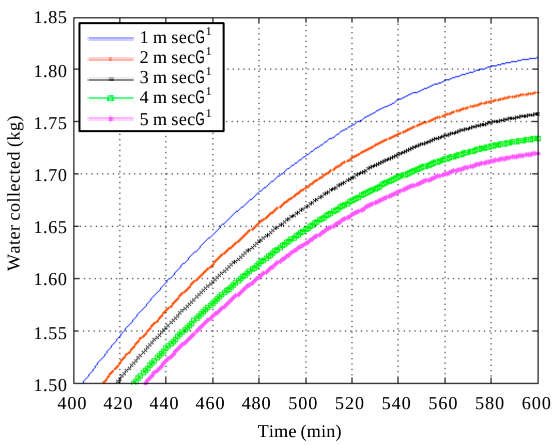

Fig. 6: Effect of wind speed to the mass flow rate during the end of simulation

CONCLUSION

The heat transfer energy balance model for single slope solar still is applied based on the heat transfer process from the basin of solar still, to the water in basin, glass cover and finally released to the surrounding. Convection, radiation, evaporation and condensation process took place in solar still operation with consideration of critical parameters identified as the slope angle, mass of water in basin and wind speed. Simulation carried out revealed the importance of the slope angle matching the latitude of the experimental location, the increasing of water mass in the basin leading to decreasing clean water produced and the presence of wind speed will help to increase the output only when the sunlight is sufficient.

ACKNOWLEDGMENTS

The authors are thankful to the Ministry of Higher Education Malaysia for funding this project (Grant No. FRG0310-TK-1/2012) and the Materials and Minerals Research Unit, School of Engineering and Information Technology, Universiti Malaysia Sabah for providing support and facilities.

NOMENCLATURE

A = Area (m^2)
a = Absorptance
G = Solar irradiance (W/m^2)
h = Heat transfer coefficient (W/m^2) (°C)
h_{fg} = Latent heat of evaporation (kJ kg^{-1}) (°C)
$(MC)_w$ = Water heat capacity rate per unit area (J m^{-2}) (°C)
$\dot{m}$ = Mass flow rate (kg sec^{-1})
η = Efficiency
q = Heat transfer rate (W m^{-2})
T = Temperature (°C)
t = Time (sec)
V = Wind Speed (m sec^{-1})
θ = Glass cover angle, °subscript
a = Ambient
b = Basin
c = Convection
evp = Evaporative
g = Glass cover
loss = Loss
r = Radiation
s = Sky
t = Total
w = Water

REFERENCES

Abdallah, S. and O.O. Badran, 2008. Sun tracking system for productivity enhancement of solar still. Desalination, 220: 669-676.

Akash, B.A., M.S. Mohsen and W. Nayfeh, 2000. Experimental study of the basin type solar still under local climate conditions. Energy Convers. Manage., 41: 883-890.

Cooper, P.I., 1973. The maximum efficiency of single-effect solar stills. Solar Energy, 15: 205-217.

Dunkle, R.V., 1961. Solar water distillation: The roof type still and a multiple effect diffusion still. Proceedings of International Conference on Heat Transfer, August 28-September 1, 1961, Colorado, USA., pp: 895-902.

Dwivedi, V.K. and G.N. Tiwari, 2009. Comparison of internal heat transfer coefficients in passive solar stills by different thermal models: An experimental validation. Desalination, 246: 304-318.

Hongfei, Z., Z. Xiaoyan, Z. Jing and W. Yuyuan, 2002. A group of improved heat and mass transfer correlations in solar stills. Energy Convers. Manage., 43: 2469-2478.

Howe, E.D., 1986. Measurements and control in solar distillation plants. Desalination, 59: 307-320.

Ismail, B.I., 2009. Design and performance of a transportable hemispherical solar still. Renewable Energy, 34: 145-150.

Kumar, S. and G.N. Tiwari, 2009. Life cycle cost analysis of single slope hybrid (PV/T) active solar still. Applied Energy, 86: 1995-2004.

Panchal, H.N. and P.K. Shah, 2011. Modelling and verification of single slope solar still using ANSYS-CFX. Int. J. Energy Environ., 2: 985-998.

Setoodeh, N., R. Rahimi and A. Ameri, 2011. Modeling and determination of heat transfer coefficient in a basin solar still using CFD. Desalination, 268: 103-110.