Mathematical Modelling of Portable Solar Water Distillation System

U. Sahoo[1,2,*], S.K. Singh[1], R. Kumar[2] and P. Kumar[3]

[1]*National Institute of Solar Energy, Ministry of New and Renewable Energy (MNRE), Gurgaon-122003, India*

[2]*Department of Mechanical Engineering, Delhi Technological University, Bawana Road, Delhi-110042, India*

[3]*UNDP-GEF CSHP, Ministry of New & Renewable Energy, Block No 14, CGO Complex, Lodi Road, Delhi-110003, India*

Abstract: Portable Solar Water Distillation (PSWD) system can provide drinking water and hot water simultaneously to households. It utilizes solar radiation to heat the water and produce fresh water out of the saline or brackish water & also produce hot water. The paper focuses mainly on field performance of a new design of PSWD for domestic applications in remote and hilly areas. Field Performance data of PSWD system has been recorded during summer and winter in northern region. It is observed that on Solar Global Radiation 2.3 kWh/ 0.25 m^2, maximum output of distilled water generation of 1.2 liters/day per 0.25 m^2 was achieved and average temperature of hot brackish water has reached 42^0C at ambient temperature of 23^0C within 8 hours. This system is the most efficient and cost effective. It can produce pure, clean fresh water along with hot brackish water from any water source.

Keywords: Solar energy, mathematical modelling of PSWD system, hot brackish water.

1. INTRODUCTION

India is endowed with a very vast solar energy potential. Most of the part of the country has good Sunshine about 200-250 days with Global Horizontal Irradiation (GHI) of 4.5-7.5 kWh/m^2/day [1-4]. When incident solar radiation is captured and transferred as heat, to perform various useful applications, is called solar thermal energy. It is easy for anyone to comprehend the role of heat from solar energy in our daily life and importance of availability of fuel in the future. The total collectors' area for solar water/air heating system amounts to 7.01 million m^2 as on March 2013 in this country. However there is a gap in the demand and supply position. It is recognized that solar thermal energy based on the various solar energy technologies can, to some extent, help in meeting the growing energy needs. On the other hand huge and growing population is putting a severe strain on all the natural sources of country. Most water resources are contaminated by sewage and agricultural runoff. Solar still is a mini natural water cycle of earth. In the water cycle, solar energy heats water in the seas and lakes, evaporates it, and condenses it as clouds to return to earth as rainwater.

India has made progress in supply of drinking water to people but gross disparity in coverage exists across the country. Although access to drinking water has increased, but as per estimation of World Bank about 21% of communicable diseases in India are related to unsafe water. It is true that providing drinking water to such a large population is an enormous challenge. It is estimated that around 37.7 million Indians are affected by waterborne diseases annually. The average availability of water is reducing steadily with the growing population and it is estimated that by 2020 India will become a water stressed nation. Ground water is the major source of water in our country with 85% of the population dependent on it [5-6]. Solar distillation is mostly used to produce fresh water from either seawater or brackish water by utilizing the freely available solar energy. Single basin solar stills represent one of the earliest designs used in this regards. Its main advantage lies in easy construction and simplicity of operation and maintenance. Portable type solar distillation is having importance as there is no installation cost and manufacturing base, spare parts & trained manpower are not required. Taking in the view NISE has developed a PSWDs for producing drinking water in remote areas including rural villages and defence establishments, hilly areas of Himalayan region and coastal areas. In this study mathematical modelling with performance analysis has been carried out.

2. PSWD SYSTEM DESCRIPTION

Figure **1** shows PSWD system, which is a simple modular design, solar distillation panel cum tank and handle cum stand. It can be installed in balconies, terraces, roofs, gardens and require a very small shadow free area. Sodha *et al.* [7] has developed new concept on multi wick solar still to increase the productive of still. They used a black jute cloth pieces

*Address correspondence to this author at the National Institute of Solar Energy, Gwalpahari, Gurgaon, Haryana-122003, India; Tel: +91- 8802760453; E-mail: uk.sec.mnre@gmail.com

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uneven length placed one upon another and separate by polyethylene film. The glass thickness is 3.0 mm. Output distilled was 2.5 liters/m2 day. Kabeel [8] investigated on a concave type wick for absorption/evaporation and pyramid shaped still were normally used for condensation. The average production of still was 4.1 liters/m2 day. A series of experimental and theoretical studies on inclined wick type solar stills are conducted by Mimaki *et al.* [9] & Tanka *et al.* [10] in Japan. They used a Black cotton towel as wick with an effective area of 1.79 m^2 and glass thickness of 5 mm, which is insulated with still. The still output recorded was 5.0 liters/m^2 day at the solar global radiation of 23 MJ/m^2. The PSWD system is design with a glazed area of 0.25 m^2, weight 6 kg and having a thin black cloth of 0.2 mm for absorbing the input water. The front glazing is of polycarbonate thin sheet (0.18 mm), which is tough, dimensionally stable, high impact resistance, good temperature capability and expected life of 8-10 years. The inlet raw water is located at the top of the system and outlet of distilled water, hot brackish water at the bottom of the system.

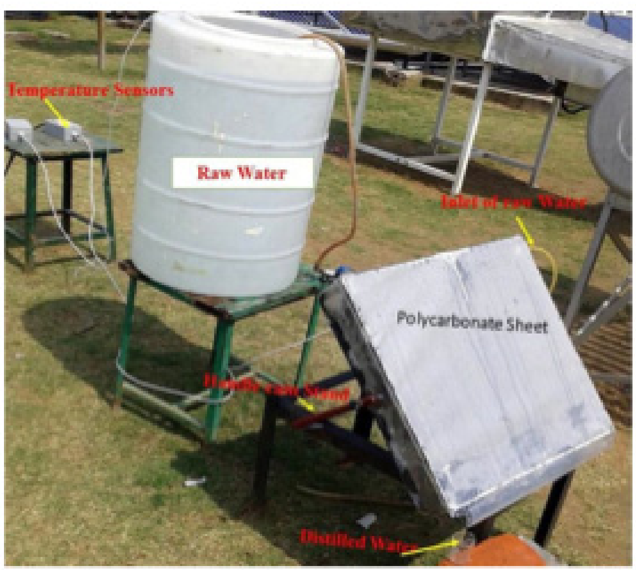

Figure 1: Experimental setup of PSWD system.

3. MATHEMATICAL MODELLING OF PSWD SYSTEM

The mathematical model of the system has been analyzed using energy balance and mass balance equations. The performance of a conventional solar distillation system can be evaluated by various methods such as iteration method, periodic transient analysis, computer simulation method and Runge-Kutta numerical method [11].

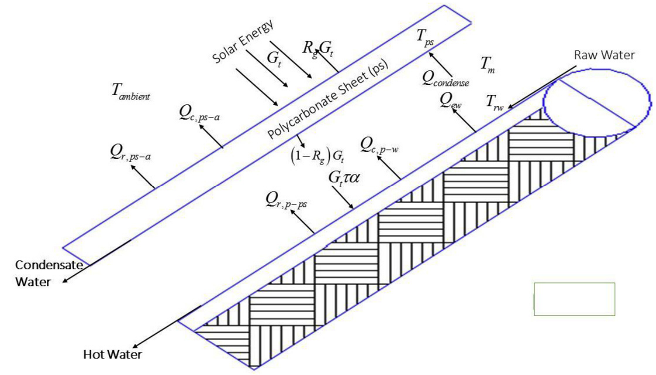

Figure 2: Schematic thermal process of the proposed system.

In the most of these method the basic internal heat and mass transfer methods, as given by Drunkle [12], are used. The energy equation for absorbing plate/cloth is expressed as;

$$m_p c_p \frac{dT}{dt} = G_t \tau\alpha - Q_{r,p-ps} - Q_{c,p-w} \tag{1}$$

The energy equation for the flowing water inside the black cloth can be defined as;

$$\rho_w c_w x \frac{dT_{w,out}}{dt} = c_w (\dot{m}_{in} T_{w,in} - \dot{m}_{out} T_{w,out}) \frac{1}{y} + Q_{c,p-w} - Q_{ew} \tag{2}$$

Where;

The outlet mass flow rate of the water.

$$\dot{m}_{out} = \dot{m}_{in} - \dot{m}_{ew} y \tag{3}$$

and mass flow rate of water evaporation $(\dot{m}_{ew})$ inside the box (kg/s per 0.25 m^2) is expressed as.

$$\dot{m}_{ew} = \frac{Q_{ew}}{h_{fg}} \tag{4}$$

hfg is latent heat of vaporization of hot water.

The energy equation for the polycarbonate sheet cover is written as

$$m_{ps} c_{ps} \frac{dT_{ps}}{dt} = Q_{r,p-ps} + Q_{cw} - Q_{r,ps-a} - Q_{c,ps-a} \tag{5}$$

Where, T_{ps} is the temperature of the polycarbonate sheet, and m_{ps} and c_{ps} are the mass and the specific heat of the polycarbonate sheet, respectively. The heat flux terms, $Q_{r,ps-a}$ and $Q_{c,ps-a}$ represent the radiation heat transfer and the convection heat transfer from the polycarbonate sheet (ps) to atmosphere at ambient temperature $T_{ambient}$.

Mass of condensed water $\left(\dot{m}_{cw}\right)$ can be calculated as;

$$\dot{m}_{cw} = \frac{Q_{cw}}{h_{fg}} \tag{6}$$

The processes of evaporation and condensation are mainly functions of relative humidity. Then, in order to calculate the evaporation and condensation heat fluxes, it is needed to know the amount of water vapor within the cavity. The vapor mass balance equation is given as

$$\frac{dm_v}{dt} = (\dot{m}_{ew} - \dot{m}_{cw})y.z \tag{7}$$

where *Mv* is the vapor mass within the cavity, and *y* and *z* are the length and the width of cavity respectively. The temperature of the air–vapor mixture (i.e., *Tav*), the partial pressure of air and vapor and the total pressure, respectively, are calculated as

$$P_a = \frac{m_a R_a T_{av}}{V} \tag{8}$$

$$P_v = \frac{m_v R_v T_{av}}{V} \;\&\; P = P_a + P_v \tag{9}$$

where V is the volume of cavity. The saturation pressure is obtained using the stated equation of $P_{sat} = P\left(T_m\right)$. The mass of air within the box is assumed to be constant.

The specific humidity and the relative humidity inside the box is defined as.

$$\omega = \frac{m_v}{m_a} \; \varphi = \frac{P_v}{P_{sat}} \tag{10}$$

The condensation heat flux within the system

$$Q_{cond} = 85.0(T_m - T_g)\varphi \tag{11}$$

where *Tm* and *Tps* are the temperatures of the air–vapor mixture and the temperature of the polycarbonate sheet, respectively.

Drunkle procedure is summarized by Tiwari *et al.* [13] (2003). According to this procedure, the hourly evaporation per square meter from solar distillation is

$$Q_{ew} = 0.0163 \cdot h_{cw}(P_w - P_{ps}) \tag{12}$$

Where, h_{cw} is convective heat transfer coefficient from water surface to polycarbonate sheet.

The partial pressure of water is expressed as

$$P_w = 100\left(0.004516 + 0.0007178 t_w - 2.649\times10^{-6} t_w^{\,2} + 6.944\times10^{-7} t_w^{\,3}\right) \tag{13}$$

And,

Partial pressure of polycarbonate sheet is defined

$$P_{ps} = 100\left(0.004516 + 0.0007178 t_{ps} - 2.649\times10^{-6} t_{ps}^{\,2} + 6.944\times10^{-7} t_{ps}^{\,3}\right) \tag{14}$$

The instantaneous efficiency is expressed as;

$$\eta_i = \frac{Q_{ew}}{G_t} \tag{15}$$

4. RESULTS AND DISCUSSIONS

The performance data of PSWDs was recorded for 8 hours a day from 9:00 hours to 17:00 hrs daily over for a period of one year. It is observed that, during the

Table 1: Parameters Taken for Design of the PSWD System

Parameters	Symbols	Value
Mass of absorber black cloth	$m_{absorber\ cloth}\ \left(kg/m^2\right)$	2.1
Absorptivity of the absorber black cloth	α	0.94
Emissivity of the absorber black cloth	ε_{cloth}	0.06
Mass of polycarbonate sheet	$m_{ps}\ \left(kg/m^2\right)$	0.8
Transmissivity of polycarbonate sheet	τ	0.8
Emissivity of polycarbonate sheet	ε	0.95
Latent heat of vaporization	$h_{fg}\ \left(kJ/kg\right)$	2260

Table 2: Amount of Fresh Water and Hot Water Obtained from Testing

Sl. No.	Distilled Water (liters/hr per m^2)	Hot Water (liters/hr per m^2)	Global Radiation (kwh/m^2)
1.	0.67	1.53	6.2
2.	0.58	1.62	5.6
3.	0.49	1.71	5.01
4.	0.37	1.83	3.78
5.	0.42	1.78	4.37

performance testing of inclined PSWD, average field data on different parameters namely temperature of cover sheet & hot brackish water (^{0}C), tilted Global radiation (kWh/m^2), wind speed (m/sec), ambient temperature, generation of fresh water and hot brackish water have been recorded.

The Table **1** shows the simulation parameters taken for design of the PSWD system.

To observe this phenomenon, the system has taken some variable which is shown in Table **2**.

The fresh water increases as tilted global radiation increase. The fresh water of 5.2 litrs/day m^2 at the titled global radiation of 6.2 kWh/m^2 has been achieved.

Figure **3** represent the comparison between the temperatures of hourly variation on polycarbonate sheet, brackish water with respect to tilt global radiation and ambient temperature. It is noted that the brackish water temperature is mostly similar to cover sheet/polycarbonate sheet temperature.

The variation of efficiency η vs. (Tw-Ta)/G (characteristics curve) for solar flat plate distillation system are shown in Figure **4**. The over all efficiency of system has improved due to the simultaneous collection of hot brackish water along with the distilled water. The portable solar water distillation system is, therefore, more advantageous as compared to other flat plate solar distillation system.

5. CONCLUSION

The PSWD system has been designed, fabricated and simulated as per Indian climatic condition for Himalayan regions and northern regions. The system generates simultaneously pure water and hot water. In this analysis several parameters are investigated like, solar tilt global radiation, hot water temperature (i.e. brackish water), mass flow rate of pure water or fresh water & flow rate of hot brackish water. The generation of fresh water of 1.4 liters/day per 0.25 m^2 and hot brackish water of 5.7 liters/day per 0.25 m^2 at temperature of 42^{0}C were achieved. It is especially useful for domestic household, remote areas and

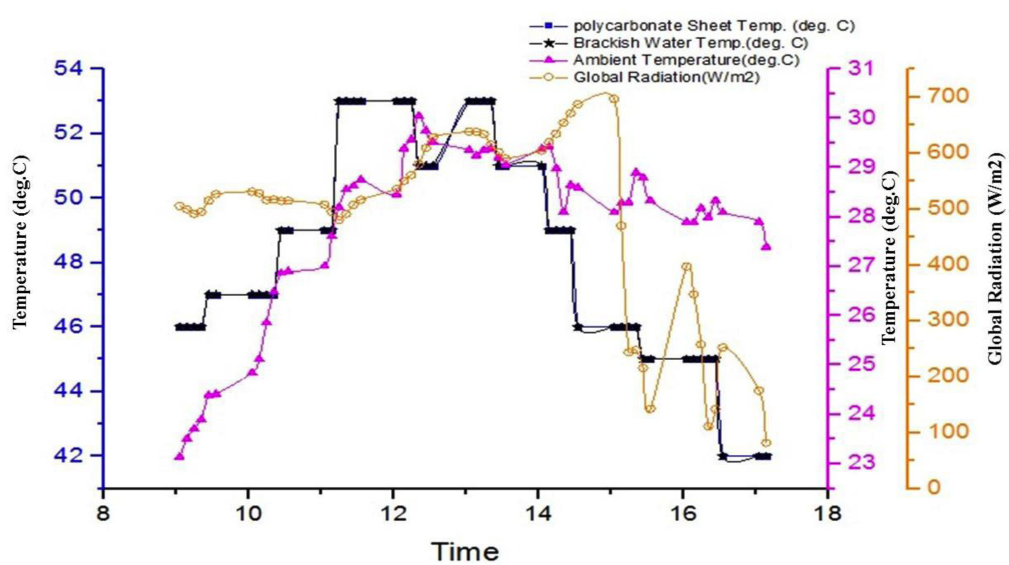

Figure 3: Hourly variation of global radiation and temperature of polycarbonate sheet, brackish water, ambient temperature with time of the day for the solar distillation system.

defence establishment which require both fresh water for drinking and hot water for different usage.

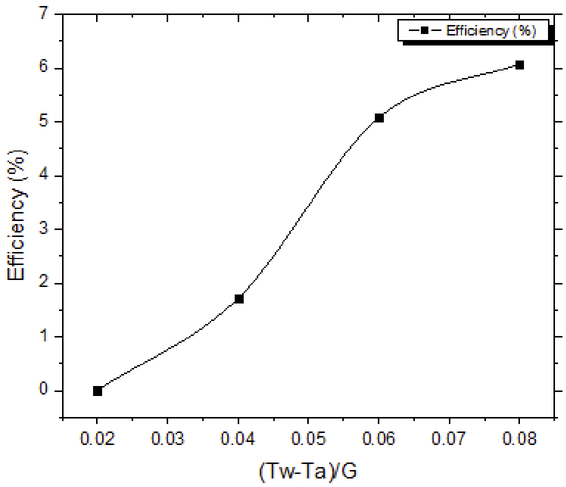

Figure 4: Characteristics curve of Distillation system.

NOMENCLATURE

m_{ap} = mass of absorbing cloth (kg/m^2)

T_p = Temperature of the absorbing cloth (^oC)

c_p = Specific heat of the absorbing cloth (kJ/kgK)

G_t = Tilted global radiation $(kWh/m^2/day)$

$Q_{r,p-ps}$ = Radiation heat transfer from plate to polycarbonate sheet

$Q_{c,p-w}$ = Convective heat transfer from plate to flowing water

$T_{w,out}$ = The outlet of water temperature on the absorber cloth (^oC)

$T_{w,in}$ = The inlet water temperature of feed water (^oC)

ρ_w = Density of water (kg/m^3)

c_w = Specific heat of water $(J/kg.^oC)$

m_{inlet} = Inlet mass flow rate of the water $(kg/\sec)$

m_{outlet} = Outlet mass flow rate of the water $(kg/\sec)$

x = thickness of the distillation box cavuty (m)

y = length of the distillation box cavity (m)

z = width of the distillation box cavity (m)

P_a = Partial pressure of air

P_v = Partial pressure of vapor

REFERENCES

[1] Market assessment of solar water heating system. Ministry of New and Renewable Energy 2011.

[2] Solar Radiation Energy over India. Indian Meteorological Department and Ministry of New and Renewable Energy, Govt. of India 2008.

[3] Sahoo UK, Singh SK, Singh JP, Sharma H, Kumar P. Design & Performance Analysis of Portable Solar Water Heating System for Rural Areas: Himalayan Regions, India. Int J Renew Energy Res 2014; 4(3): 743-8.

[4] Jawaharlal Nehru National Solar Mission phase-I. Ministry of New and Renewable Energy, India 2011-12.

[5] Kumar CP. Fresh water resources: a perspective,Aviailable from: http://www.angelfire.com/bc/nihhrrc/documents/fresh.html

[6] Drinking water quality in rural India: Issues and Approach, Avilable from: http://www.wateraid.org/~/media/Publications/drinking-water-quality-rural-india.pdf

[7] Sodha MS, Kumar A, Tiwari GN, Tyagi RC. Simple multiple wick solar still: analysis and performance. Solar Energy 1981; 26: 127-31.

[8] Kabeel AE. Performance of solar stills with a concave wick evaporation surface. Energy 2009; 34: 1504-09. http://dx.doi.org/10.1016/j.energy.2009.06.050

[9] Mimaki M, Tanaka K, Watanabe K. The performance of solar stills. Energy Developments in Japan 1981; 3: 207-5.

[10] Tanaka K, Yamashita A, Watanabe K. Experimental and analytical study of the tilted wick type solar still. Solar World forum. Proc. ISES Congress, August 1981 (Ed. D.O. Hall & J.Marton). Pergamon Press 1981; 1087-91.

[11] Aybar HS. Mathematical modelling of an inclined solar water distillation system. Desalination 2006; 190: 63-70. http://dx.doi.org/10.1016/j.desal.2005.07.015

[12] Dunkle RV. Solar Water Distillation System: the roof top style and multiple effect diffusion still. Int. development in heat transfer ASME. In: Proceeding of Int. heat transfer, Part V. University of Colorado 1961; 890-5.

[13] Tiwari GN, Singh HN, Tripathi R. Present Status of Solar Distillation. Solar Energy 2003; 75(5): 367-3. http://dx.doi.org/10.1016/j.solener.2003.07.005

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