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Study of Solar Desalination System with Evaporative Porous Surface in Basin to Meet out Drinking Water Requirement of Remote Area Dwellers of Rajasthan

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Abstract: Desalination is a technique used to produce potable water from water sources containing dissolved chemicals contamination. Water with TDS value (mg/L) less than 1000 is called potable and water with TDS value (mg/L) >1000 is called brackish water. There are several methods of water desalination like ion exchange, electro dialysis, reverse osmosis, distillation, solar desalination etc.

Solar desalination is a process in which solar energy is used to evaporate brackish water in an air-tight chamber and allowed to condense on a condensing surface, leaving behind the dissolved impurities to make it suitable for drinking. States of India like Rajasthan with highly contaminated ground water and ample solar radiations may use this technique to produce drinking water from the available brackish water.

In this paper a mathematical model is presented to theoretically predict the output of a solar desalination system by enhancing the evaporative surface area which is verified experimentally. It is observed that efficiency of solar desalination system may be increased by increasing the surface area available for evaporation.

Key words: Solar still, porous surface, potable water, enhanced surface.

Introduction

Water which is a basic human need is also a very limited natural resource. In the recent decades, human demand and misuse of water resources have continued to grow. Therefore, water security for human life has become a matter of principal concern for sustainable development in the 21st century. It is estimated that 20% of the world population still lack access to safe drinking water. In Asia, as per Rajat Choudhary (1998), one in three persons lacks access to safe drinking water and nearly five lakh infants die each year from water-related diseases and lack of adequate water and sanitation.

Sufficient quantity of drinking water which should be microbiologically and chemically safe is primary health requirement. Water is considered microbiologically safe if in a sample of 100 mL coliform count comes out be less than 10.

There are different levels of risk associated with different chemicals dissolved in water. The most widespread and significant naturally occurring water-borne toxics are arsenic and fluoride (guideline maximum concentrations of 10 μg/L and 1.5 mg/L respectively). Fluoride problems exist in 150 districts of 17 states in the country with Orissa and Rajasthan the most severely affected. Excessive fluoride in drinking water causes fluorosis, manifested in weak bones, weak teeth and anaemia. The calamity of arsenic – a poison and a carcinogen – in the ground waters of the Gangetic delta, affecting at least 35 million people in West Bengal, Bihar and Bangladesh, is by now well known (Bassam et al., 1997).

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Present Status of Drinking Water in Rajasthan

Rajasthan is the largest state in India, occupying over 10% of the total area of the country with about 5% population but possesses only about 1.16% of country's water resources. Rajasthan has two-third of area as desert and it faces scarcity in rainfall, and recurring droughts in 3-4 years in a cycle of five years. Out of 236 groundwater blocks in Rajasthan, only 49 are safe in terms of ground water while 101 are critical/semi-critical and 86 are over-exploited. About 21,190 villages/habitations suffer from the problem of excessive salinity, 23,297 villages/ habitations suffer from excess fluoride problems and 20,659 villages/habitations suffer from excessive nitrate problem. As per State Rural Drinking Water & Sanitation Policy (2005), it reveals that groundwater exploitation has increased from 59% to 105% i.e. by 46%, which has resulted in depletion of water level as well as deterioration in water quality. Tremendous use of ground water has brought adverse changes in the geochemistry of water. Natural contaminants such as fluoride, nitrate, and chloride salts are increasing in ground water making it unfit for drinking and posing risk to health.

Water samples from different water sources of a village is taken for analysis which is reported in Tables 1 and 2. The village selected for the work is Chui, situated 70 kms south-east of the district headquarters, Nagaur and around 220 kms west of the state capital, Jaipur.

Rajasthan by its location is endowed with plentiful and almost uninterrupted supply of sunshine throughout the year especially in non-monsoon months. About 7.5 kwh/m^2/day of solar energy is received daily over the state as a whole. Part of this energy can be used for solar distillation to meet out the demand of drinking water.

Different Methods of Providing Drinking Water

Drilling, reticulation, trucking etc. are different methods used by the state Government in its effort to provide safe drinking water to every household. Drilling is most satisfactory in the long term and preferred method for the remote areas but it involves high investment due to very low groundwater level in many of the parts. Apart from investment chemically contaminated salty water is found more often than fresh water. This method cannot

Table 1: Physico-chemical analysis of water samples from selected village

S. No.	*Name of test*	*Actual test result found*			*Standard requirements*
		Sample I	*Sample II*	*Sample III*	
1	pH value (at 25° C)	7.4	8.2	8.3	6.50-8.50
2	Total solids	3315 PPM	2665 PPM	2925 PPM	NMT 500 PPM
3	Total dissolved solids	3295 PPM	2640 PPM	2895 PPM	NMT 500 PPM
4	Total suspended solids	20 PPM	25 PPM	30 PPM	NMT NIL
5	Total hardness	1490 PPM	1525 PPM	1750PPM	NMT 300 PPM
6	Calcium hardness	895 PPM	935 PPM	980 PPM	NMT 180 PPM
7	Magnesium hardness	595 PPM	590 PPM	770 PPM	NMT 120 PPM
8	Fluoride (F)	2.82 PPM	3.25 PPM	3.10 PPM	NMT 1.00 PPM
9	Nitrate (NO_3)	19.2 PPM	19.2 PPM	18.6 PPM	NMT 45 PPM
10	Odour	Odourless	Odourless	Odourless	Agreeable
11	Colour	0.50 HZN	0.50 HZN	0.60 HZN	NMT 5 HZN
12	Turbidity	1.10 NTU	1.20 NTU	1.12 NTU	NMT 5 NTU
13	Taste	Saline	Saline	Saline	Agreeable

Table 2: Bacteriological examination of water samples

Name of test	*Actual test result found*			*Standard requirements*
	Sample I	*Sample II*	*Sample III*	
Total Coliform Bacteria	25 Coliform per 100 mL	70 Coliform per 100 mL	51 Coliform per 100 mL	NMT 10 Coliform per 100 mL

be used in areas with very low water table and has been declared dark zone by the government in which groundwater depletion is not allowed.

Reticulation is the process by which water is brought from a borehole to the end user by pipeline. This is very satisfactory if a suitable borehole is not too far. For the scattered population this method is not economically viable. The second obstacle to reticulation is that most remote settlements do not have access to sweet boreholes in their close vicinity and, where the boreholes exist, their output is usually in use.

Trucking water is the simplest, but most expensive, and least reliable solution to the problem. In this process water is transported from source to the end users in tankers.

Since most of the rural population of the state lives in scattered locations called Dhanis/Majra/Naglas consisting of 5-10 houses only, it is very difficult to provide water to them due to their scattered habitations. Under these circumstances, there is an essential need to get potable water from the saline/brackish water, as and where water is present either on or inside the earth. There are several desalination methods like reverse osmosis, electrodialysis, ion exchange, electrical distillation, solar still etc. which are used for purification of water. All these techniques have limited applications due to one or other reasons. Among these, the solar stills can be used as desalinates, especially in Rajasthan remote settlements where brackish water is the only available option, electric or other power is scare and overall demand of habitations in terms of water is quite less and solar energy is available in abundance.

Basic Principle

Solar still has an airtight basin, usually constructed out of concrete/cement, galvanized iron sheet (GI) or fiber-reinforced plastic (FRP) with a top cover of transparent material like glass, plastic etc. The inner surface of the rectangular base is blackened to efficiently absorb the solar radiation, incident at the surface. There is a provision to collect the distillate at lower end of the glass cover. The brackish or saline water is fed into the basin for purification.

The solar radiation, after reflection and absorption by the glass cover, is transmitted inside an enclosure of the distiller unit. This transmitted radiation is further partially reflected and absorbed by the water mass. The solar radiation reaches the blackened surface and is mostly absorbed. After absorption of solar radiation at the blackened surface, most of the thermal energy is convected to water mass and a small quantity is lost to the atmosphere, by conduction. Consequently, the water gets heated, leading to its evaporation.

The evaporated water gets condensed on the inner surface of the glass cover after releasing the latent heat. The condensed water trickles into the channels provided at the lower ends of glass cover, under gravity. The collected water in the channel is taken out in some container.

Number of improved designs have been reported in literatures to increase the efficiency of the solar still like: Single-slope solar still with passive condenser, Double condensing chamber solar still by Tiwari et al. (1997), Vertical solar still by Kiatsiriroat (1989), Inverted absorber solar still by Suneja and Tiwari (1999), Multi-wick solar still by Sodha et al. (1981), and Multiple effects solar still by Tanaka et al. (2000). The basic concepts behind these models in increasing the efficiency is that the solar still should maintain: a high feed (undistilled) water temperature, a large temperature difference between feed water and condensing surface, low vapour leakage etc.

In the present work, a theoretical analysis is presented to improve the efficiency of conventional single slope solar still by enhancing the evaporative surface area. It is observed that by increasing the evaporative surface output may be enhanced and hence the efficiency of the system is on the same lines as reported by A. Bassam et al. (2003).

Theory

Expression for Mass of Distillate Collected

The mass of distillate collected per unit time from evaporating surface of area A is given as:

$$m = h \times \Delta T \times A/L \quad (1)$$

where ΔT is temperature difference between evaporative and condensing surfaces i.e. $\Delta T = T_w - T_g$

In the present communication it is proposed that vertical cotton wicks working as porous material is placed in the basin of the still. The water will rise in the wick due to capillary action. Evaporation takes place from this surface also apart from evaporation from water surface; so, the net amount of distillate collected will be the sum of water evaporated from water in the basin (m_{ew}) and from the water in the wick (m_{ep}).

$$m = m_{ew} + m_{ep} \quad (2)$$

Substituting value of m from equation (1) to equation (2)

$$m = h_{ew} \times A_w \times \Delta T/L + h_{ep} \times A_p \times \Delta T/\mathrm{L}$$
$$= \Delta T \times (A_w h_{ew} + A_p h_{ep})/\mathrm{L} \quad (3)$$

Theoretical value of mass of distillate can be predicted if evaporative heat loss coefficient from water surface (h_{ew}) and porous surface (h_{ep}) is calculated. Methods to calculate these coefficients are discussed below.

Expression for Evaporative Loss Coefficient from Water (h_{ew})

The evaporative heat transfer coefficient from water surface (h_{ew}) is given by the expression

$$h_{ew} = 16.273 \times 10^{-3}\ h_{cw} \frac{P_w - P_g}{T_w - T_g} \tag{4}$$

Value of h_{cw}, the convective coefficient, may be obtained from the following relation derived by Dunkle (1961).

$$h_{cw} = 0.884\ [T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w}]^{1/3} \tag{5}$$

So, the mass of distillate collected from A_w area of water in the basin in one hour may be given as

$$m_{ew} = 0.016273 \times h_{cw} \times (P_w - P_g) \times 3600 \times A_w/L \tag{6}$$

Expression for Evaporative Loss Coefficient (h_{ep})

Evaporative loss coefficient from the porous evaporative surface may be predicted once the value of convective coefficient h_{cp} for the porous surface is calculated.

This may be experimentally predicted by finding C and n from the empirical relation

$$\text{Nu} = C(GrPr)^n \tag{7}$$

$$h_{cp} = (k/X) \times C(GrPr)^n \tag{8}$$

$$Gr = \frac{g\beta'\rho^2 X^3 \Delta T}{\mu^2} = \frac{g\beta' X^3 \Delta T}{v^2} \tag{9}$$

$$\beta' = 1/(T_f + 273) \tag{10}$$

$$T_f = \frac{(Tw + Tg)}{2}$$

The rate of heat utilized to evaporate water from porous surface (q_{ep}) is given as in eq. (5)

$$q_{ev} = 0.016\ h_{cp}\ [P_p - \gamma P_g] \tag{11}$$

Substituting h_{cp} from equation (8) to equation (11)

$$q_{ev} = 0.016\ (k/X) \times C(GrPr)^n\ [P_p - \gamma P_g] \tag{12}$$

The mass of distillate is determined by dividing equation (12) by latent heat of vaporization and multiplying it by area of porous evaporative surface (A_p) and time interval (t).

$$m_{ep} = 0.016\ (k/X) \times C(GrPr)^n\ [P_p - \gamma P_g]\ A_p\ t$$

$$m_{ep}/R = C\ (GrPr)^n$$

where $R = 0.016\ (k/X) \times C(GrPr)^n\ [P_p - \gamma P_g]\ A_p\ t$.

The above equation may be written in form of

$$y = ax^b$$

Using the linear regression analysis the coefficient a' and b' can be obtained using which values of C and n can be obtained.

Computing Technique

Mass of distillate due to porous surface (m_{ep}), temperature of evaporating surface (T_p) and temperature of glass cover (T_g) are calculated experimentally at a time interval of one hour. *Gr* and *Pr* are calculated using the temperature dependent physical property of humid air from steam table at the film temperature.

The m_{ep}, the mass of water evaporated from the porous surface is calculated by finding the difference of mass of water calculated from solar still with evaporative surface and mass of water collected from an identical reference still placed under the identical conditions. The theoretical value of distillate collected after one hour from unit area of evaporative porous surface may be given as

$$m_{ep} = 0.016273 \times h_{cp} \times (P_w - P_g) \times 3600/L \tag{13}$$

Experimental Investigation

Construction and Experimental Setup

A photograph of a single slope solar still is shown in Figure 1. A single basin solar still is made by 19 mm thick wooden board. The base of the basin was 50 cm × 54 cm. For preventing the leakages and to improve the life of wooden box GI sheet of thickness 0.5 mm is press fitted inside the box up to 10 cm height. The corners were brazed to prevent leakages. For inlet of brackish water a socket of diameter 1.75 cm and length 15 cm is fitted at the back vertical side and a plastic container is attached in the outer side of the socket to maintain the water level. To collect distillate an aluminum channel of width 1″ and length 50 cm is fixed on smaller vertical side of the still and sloped portion of the transparent glass plate is rested on it. For achieving the green house inside the box, it is covered with a 4 mm thick window glass sheet of size 48 cm × 56 cm with an inclination of 15°, fixed to the vertical wall of the still. To ensure that vapours are not lost to the atmosphere, the glass cover is sealed with window putty (chalk and linseed oil) and brown adhesive tape. Three separate holes are also drilled in the body of the still to fix thermocouples to sense the

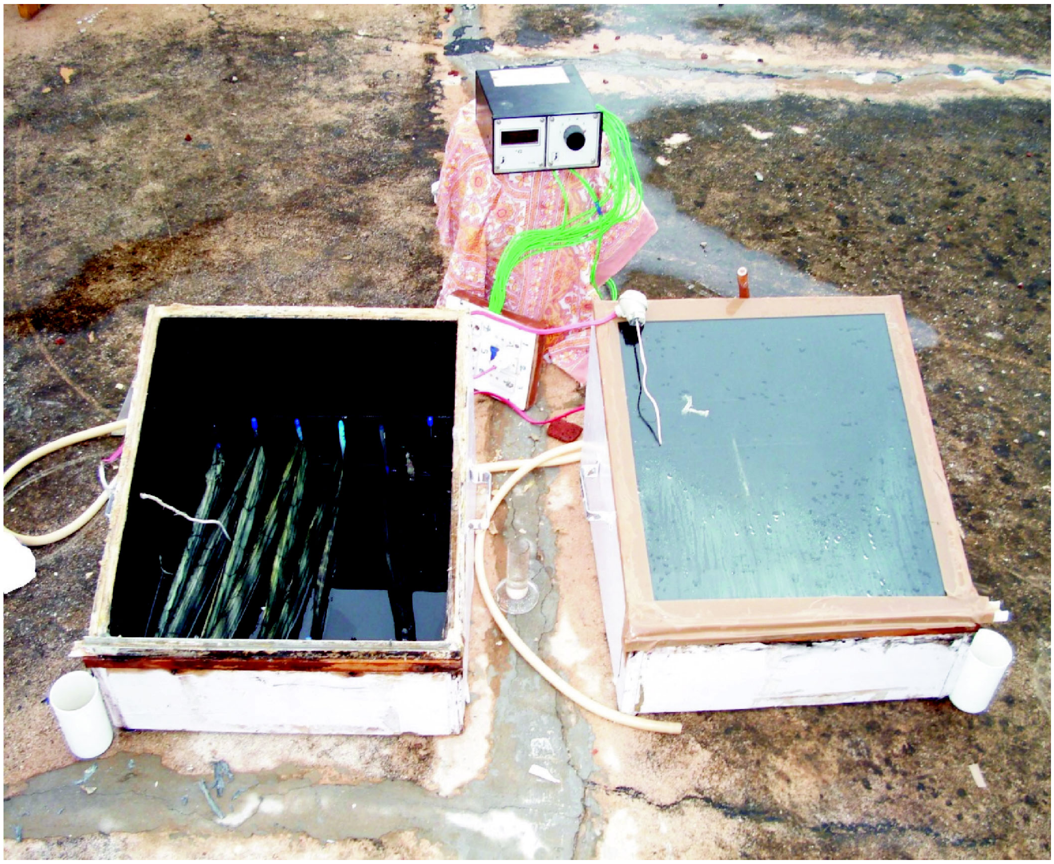

Figure 1: Inside view and top view of still with vertical evaporating surface.

temperature of water inside the basin, of porous evaporating surface and glass temperature. The solar still is oriented due south to receive maximum solar radiation throughout the year. This still is referred as Reference Still. An identical still is also constructed with vertical cotton strips of length about 3 m and width of 0.1 m placed inside the still. 0.05 m of strip was dipped inside basin water and remaining 0.05 m was exposed to air inside the still for evaporation of water to take place. The colour of strip was made black to allow it to absorb maximum radiations.

Experimental Observations

The temperature of glass cover, porous surface and water is measured with the help of thermocouples connected to digital indicator at an interval of one hour. It was observed that the temperature of porous surface was same as that of water surface of basin.

Mass of distillate collected from reference and experimental still is taken with the help of measuring cylinder at the end of each hour. All these observations are plotted in Figure 2. Ambient air temperature and solar intensity $I(t)$ is measured at a time interval of one hour with the help of thermocouple and solar intensity meter.

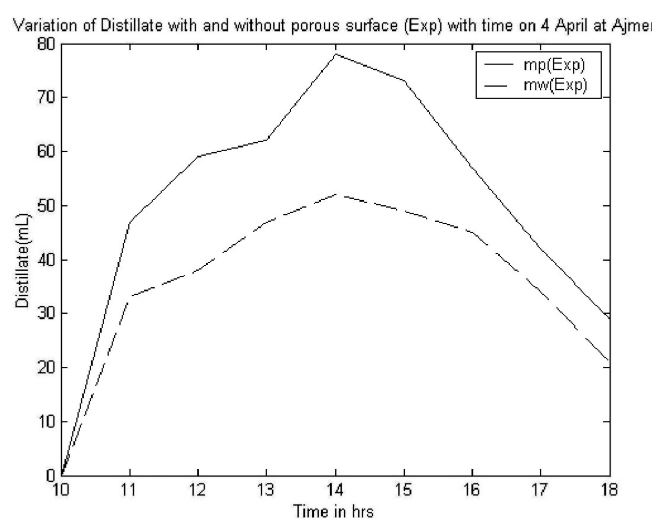

Figure 2: Experimental variation of mass of distillate with and without porous surface.

Theoretical value of mass of distillate from reference and experimental still is calculated from the theory given

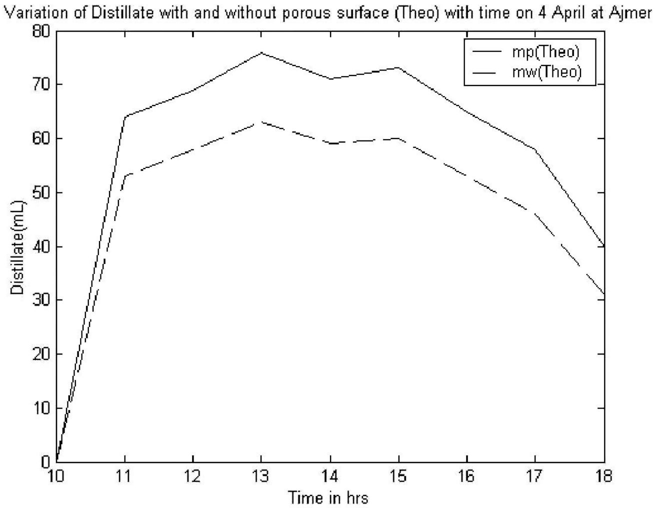

Figure 3: Theoretical variation of mass of distillate with and without porous surface.

above. The theoretical value of temperature of glass and water surface (which was found same as that of porous surface) is calculated by solving the energy balance equations of solar still using a MATLAB program. The result obtained is plotted in Figure 3.

Result and Discussion

Analysis of water samples collected from three sources of selected village is presented in Tables 1 and 2. It is observed that the available water is highly contaminated both chemically and microbiologically. This is the main reason for poor health of village population. Since the available water is not potable, it is essential to purify it to make it potable.

Solar desalination unit with improved efficiency may be used to solve the water problem of selected village. The experimental and theoretical hourly mass of distillate collected with porous surface (m_p) and without porous surface (m_w) is plotted in Figures 2 and 3. It is observed that mass of distillate collected with porous surface is more than that of without porous surface. Observations were taken on a sunny day of April at Ajmer and nearby places of selected villages.

Conclusion

Rajasthan, the desert state of India, is suffering from poor water quality due to low rainfall. Since the population density of the state is very low it is difficult for the government to supply drinking water from available conventional methods. Under these circumstances solar desalination system with improved efficiency may be a good alternative to provide potable water to remote area dwellers of the state.

The available passive solar desalination system is not successful due to their low efficiency. It is observed from the present communication that the efficiency of passive solar still may be increased by around 20% without increasing the cost of system.

Such high efficiency solar desalination system may be used to solve the drinking water crises of state.

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