Present status of solar distillation

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Abstract

In this communication an attempt has been made to review, in brief, work on solar distillation, its present status in the world today and its future perspective. The review also includes water sources, water demand, availability of potable water and purification methods including the state of art and historical background. The classification of distillation units has been done on the basis of literature survey till today. The basic heat and mass transfer relation responsible for developing, testing procedure for various designs of solar stills have also been discussed. The present status of solar distillation units in India, economics of single and double slope fibre re-inforced plastic on the basis of long-term performance and recommendations for future have been discussed in brief.

1. Introduction

More than two-third of the earth's surface is covered with water. Most of the available water is either present as seawater or icebergs in the Polar Regions. More than 97% of the earth's water is salty; rest around 2.6% is fresh water. Less than 1% fresh water is within human reach. Even this small fraction is believed to be adequate to support life and vegetation on earth. Nature itself provides most of the required fresh water, through hydrological cycle. A very large-scale process of solar distillation naturally produces fresh water. The essential features of this process are thus summarized as the production of vapours above the surface of the liquids, the transport of vapours by winds, the cooling of air-vapour mixture, condensation and precipitation. This natural process is copied on a small scale in basin type solar stills.

As the available fresh water is fixed on earth and its demand is increasing day by day due to increasing population and rapidly increasing of industry, hence there is an essential and earnest need to get fresh water from the saline/brackish water present on or inside the earth. This process of getting fresh water from saline/brackish water can be done easily and economically by desalination.

According to World Health Organization (WHO), the permissible limit of salinity in water is 500 ppm and for special cases up to 1000 ppm while most of the water available on earth has the salinity up to 10,000 ppm whereas seawater normally has salinity in the range of 35,000-45,000 ppm in the form of total dissolved salts.

Excess brackishness causes the problem of taste, stomach problems and laxative effects. One of the control measures includes supply of water with total dissolved solids within permissible limits of 500 ppm or less. This is accomplished by several desalination methods like reverse osmosis, electro dialysis, vapour compression, multistage flash distillation, multiple-effect distillation and solar distillation, which are used for purification of water. Among these, the solar stills can be used as desalinators for such remote settlements where salty water is the only type of moisture available, power is scarce and demand is less than 200 m^3/day. On the other hand, setting of water pipelines for such areas is uneconomical and delivery by truck is unreliable and expensive. Since other desalination plants are uneconomical for low-capacity fresh water demand, under these situations, solar stills are viewed as means to attain self-reliance and ensure regular supply of water.

Nomenclature

C	constant
d	average spacing between water and glass surface (m)
d_w	depth of the water (m)
F^0	solar still efficiency factor (dimensionless)
Gr	Grashof number (dimensionless)
h	convective heat transfer coefficient from basin liner to water (W/m^2 °C)
/few	convective heat transfer coefficient from water surface to glass (W/m^2 °C)
i	rate of interest (%)
IðtÞ	solar radiation intensity (W/m^2)
k	thermal conductivity (W/m °C)
L	latent heat of vaporization (J/kg)
fii.	yield of still per unit area per hour (kg/m^2/hr)
n	constant
Nu	Nusselt number (dimensionless)
P	initial cost
P_g	partial vapour pressure at glass temperature (N/m^2)
Pr	Prandtl number (dimensionless)
Pv,	partial vapour pressure at water temperature (N/m^2)
$\dot{q}_{cg}$	convective heat transfer rate from glass to ambient (W/m^2)
$\dot{q}_{cw}$	convective heat transfer rate from water surface to glass cover (W/m^2)
$\dot{q}_{ew}$	evaporative heat transfer rate from water surface to glass cover (W/m^2)
$\dot{q}_{rg}$	radiative heat transfer rate from glass to ambient (W/m^2)
$\dot{q}_{rw}$	radiative heat transfer rate from water surface to glass cover (W/m^2)
R	defined constant in Eq. (5)
R_g	reflectivity of the glass (dimensionless)
R_w	reflectivity of water (dimensionless)
T_a	ambient air temperature (°C)
T_b	basin temperature (°C)
T_g	average glass temperature (°C)
T_w	average water temperature (°C)
T_{w0}	temperature of basin water at $t = 0$ (°C)
U_L	overall heat transfer coefficient (W/m^2 °C)
UA	unacost
<	total absorptance at basin liner
a_g	absorptance of glass
<	total absorptance at water mass
Þ e f f	effective absorptance-transmittance product
8	emittance (dimensionless)
η_i	instantaneous efficiency of solar still (dimensionless)
Dt	temperature difference (°C)
x	effective transmittance after reflection and absorption from glass

Among the non-conventional methods to disinfect the polluted water, the most prominent method is the 'solar distillation'. Comparatively this requires simple technology as no skilled workers needed and low maintenance due to which it can be used anywhere with lesser number of problems.

2. Historical review

As early as in the fourth century B.C., Aristotle described a method to evaporate impure water and then condense it for potable use. However, historically the earliest documented work on solar distillation was by Arab alchemists in the 16th century (Mouchot, 1869). Della Porta (1589) used wide earthen pots, as shown in Fig. 1, exposed to the intense heat of the solar rays to evaporate water and collect the condensate into vases placed underneath (Nebbia and Mennozi, 1966).

Talbert et al. (1970) gave an excellent historical review of solar distillation. Delyannis and Delyannis (1973) reviewed the major solar distillation plants around the world. This review also included the work of Delyannis (1965), Delyannis and Piperoglou (1968), and Delyannis and Delyannis (1970). Malik et al. (1982) reviewed the work on passive solar distillation system till 1982 and this was updated up to 1992 by Tiwari (1992), which also included active solar distillation. Delyannis (1987) reviewed the status of solar assisted desalination.

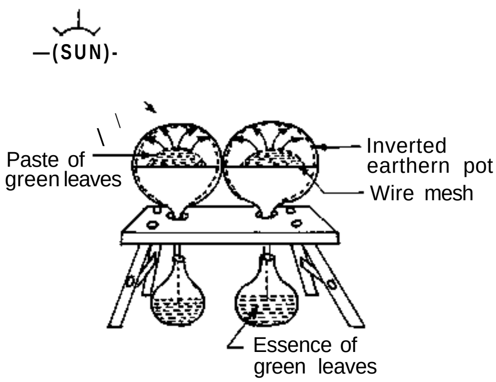

Fig. 1. Historical solar distillation apparatus.

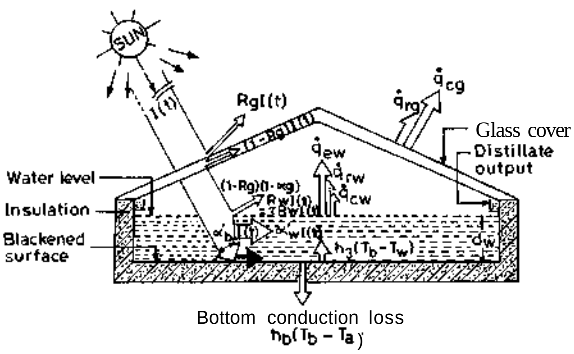

Fig. 2. Fraction of solar flux at different components of the distillation unit.

Gomkale (1988) studied in detail the solar distillation systems as per Indian scenario. Fath (1998) reviewed various designs of solar stills and studied the suitability of solar stills for providing potable water.

3. Principle of solar distillation: a state of the art

Fig. 2 shows the various components of energy balance and thermal energy loss in a conventional double slope symmetrical solar distillation unit (also known as roof type or greenhouse type). It is an air tight basin, usually constructed out of concrete/cement, galvanized iron sheet (GI) or fibre re-inforced plastic (FRP) with a top cover of transparent material like glass, plastic etc. The inner surface of the base known as basin liner is blackened to efficiently absorb the solar radiation incident on it. There is a provision to collect distillate output at lower ends of top cover. The brackish or saline water is fed inside the basin for purification using solar energy.

The performance of a conventional solar distillation system can be predicted by various methods such as, computer simulation (Cooper, 1969), thermic circuit and the sankey-diagrams (Frick, 1970), periodic and transient analysis (Cooper, 1970; Nayak et al., 1980; Sodha et al., 1980; Tiwari and Bapeswar Rao, 1983; El-Sayed, 1983; Tiwari and Madhuri, 1987), iteration methods (Toure and Meukam, 1997), numerical methods (Lof et al., 1961; Sartori, 1987; Sharma and Mullick, 1991).

In most of the above-mentioned methods, the basic internal heat and mass transfer relations, given by Dunkle (1961), has been used.

4. Distillate output

Following Dunkle (1961), the hourly evaporation per m^2 from solar still is given by

$$\dot q_{ew} = 0.016 h_{cw}(P_w - P_g) \qquad (1)$$

where

$$Nu = \frac{h_{cw} d}{k} = C(Gr \cdot Pr)^n \qquad (2)$$

The hourly distillate output per m^2 from a distiller unit is given by

$$\dot m_w = \frac{\dot q_{ew}}{L} \times 3600 = 0.0163(P_w - P_g)\left(\frac{k}{d}\right)\left(\frac{3600}{L}\right)C(Gr\,Pr)^n \qquad (3)$$

$$\frac{\dot m_w}{R} = C(Gr\,Pr)^n \qquad (4)$$

where

$$R = 0.0163(P_w - P_g)\left(\frac{k}{d}\right)\left(\frac{3600}{L}\right) \qquad (5)$$

The constants C and n are calculated by regression analysis for known hourly distillate output (Dunkle, 1961), water and condensing cover temperatures and design parameters for any shape and size of solar stills (Kumar and Tiwari, 1996).

5. Classification of solar distillation systems

On the basis of various modifications and mode of operations introduced in conventional solar stills, these solar distillation systems are classified as passive and active solar stills. In the case of active solar stills, an extra-thermal energy by external mode is fed into the basin of passive solar still for faster evaporation. The external mode may be collector/concentrator panel (Rai and Tiwari, 1982; Fernandez and Chargoy, 1990; Lawrence and Tiwari, 1990; Zaki et al., 1992; Kudish et al., 2002), waste thermal energy from any chemical/industrial plant (Tleimat and Howe, 1966) etc. If no such external mode is used then that type of solar still is known as passive solar still (Bloemer et al., 1965; Kudish, 1982; Delyannis and Delyannis, 1983; Tiwari et al., 1986; Yadav and Tiwari, 1987; Clark, 1990).

Different types of solar still available in the literature are conventional Solar Stills, Single-slope Solar Still with Passive Condenser, Double Condensing Chamber Solar Still (Tiwari et al., 1997), Vertical Solar Still (Coffey, 1975; Kiatsiriroat et al., 1987; Kiatsiriroat, 1989), Conical Solar Still (Tleimat and Howe, 1967), Inverted Absorber Solar Still (Suneja and Tiwari, 1999), Multi-Wick Solar Still (Frick and Sommerfeld, 1973; Sodha et al., 1981; Tiwari, 1984), Multiple Effect Solar Still (Barrera, 1993; Franco and Saravia, 1994; Adhikari et al., 1995; Fath, 1996; Tanaka et al., 2000a,b).

Figs. 3 and 4 show the cross-sectional view of FRP multi-wick solar still (Sodha et al., 1981; Tiwari and

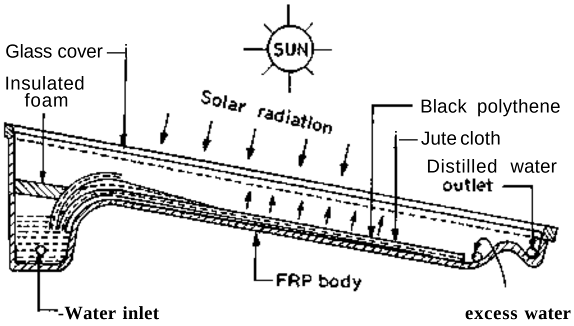

Fig. 3. Cross-sectional view of FRP multi-wick solar still.

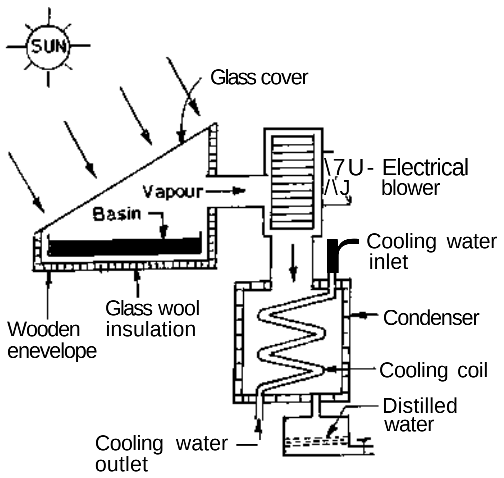

Fig. 4. Hybrid solar distillation system.

Salem, 1984; Tiwari et al., 1986) and a hybrid solar distillation system (Varol and Yazar, 1996) respectively. FRP multi-wick solar still explains the passive mode while the hybrid solar distillation system explains the active mode of solar still.

6. Performance of solar still

Following Tiwari (2002), the instantaneous efficiency of a distiller unit is given as

$$n_i l = W) = W) \quad (6)$$

Simplifying above equation we can write

$$\eta_i = F'\left[(\alpha\tau)'_{\text{eff}} + U'_L\left(\frac{T_{w0} - T_a}{I(t)}\right)\right] \quad (7)$$

where

$$U_L \; 0 \; C/_L[\exp(-a \cdot At)] \quad (8)$$

Above equation describes the characteristic curve of a solar still in terms of solar still efficiency factor (F^0), effective transmittivity-absorptivity product [(at)^] and overall heat loss coefficient (U_L) (Tiwari and Noor, 1996).

A detailed analysis of the equations of ^ justifies that the overall top loss coefficient (UL) should be maximum for faster evaporation that will result in higher distillate output.

The meteorological parameters namely wind velocity (Soliman, 1972), solar radiation, sky temperature, ambient temperature, salt concentration, algae formation on water and mineral layers on basin liner affect significantly the performance of solar stills (Garg and Mann, 1976).

For better performance of a conventional solar still, following modifications were suggested by various researchers: reducing bottom loss coefficient (Cooper, 1969; Tiwari and Madhuri, 1987), reducing water depth in basin/multi-wick solar still (Tiwari and Madhuri, 1987; Yadav and Tiwari, 1989; Lawrence et al., 1990), using reflector (Wibulswas and Tadtium, 1984; Tamini, 1987), using internal (Ahmed, 1988) and external condensers (Fatani and Zaki, 1995), using back wall with cotton cloth (Wibulswas and Tadtium, 1984), use of dye (Rajvanshi and Hsieh, 1979; Sodha et al., 1980; Rajvanshi, 1981; Lawrence et al., 1988), use of charcoal (Naima and Kawi, 2002a,b), use of energy storage element (Naima and Kawi, 2002a,b), use of sponge cubes (Bassam et al., 2003), multi-wick solar still (Sodha et al., 1981), condensing cover cooling (Bapeshwar and Tiwari, 1984; Tiwari and Prasad, 1996; Bassam et al., 1997), inclined solar still (Malik et al., 1982), increasing evaporative area (Kwatra, 1996).

It is observed that there is about 10-15% effect in overall daily yield due to change of climatic and operational parameters within the expected range.

7. Global status of solar distillation

As per documented literature survey, most of distillation systems have been abandoned due to very slow production rate. However, research in the area of solar distillation is limited in the following academic organizations namely IIT Delhi, CAZRI, Jodhpur, and SPRERI, Anand (India); UNAM Ciudad Universitaria, Coyoacáan (Mexico); RYUKYUS, NAGOYA and CHUO Universities (Japan); BEN-GURION University of the Negev (Israel); TECHNISCHE Universitat Bergakademie Freiberg (Germany); ALEXANDRIA University (Egypt); Jordan University of Science and Technology, Irbid (Jordan); University of Ouargla (Algeria); XiAn Jiao Tong University (China); University of Foggia (Italy); NCSR "DEMOKRITOS"

Laboratory for Solar and other Energy Systems (Greece).

8. Economic evaluation

It is very important to conduct economic analysis and evaluation of an engineering system to test its techno-economic and socio-viability. The solar distillation engineering system is meant to get distilled water for various purposes. The cost of the water produced depends on the capital cost of equipment, the cost of the energy and the operation and maintenance cost other than energy. In the case of solar stills, the cost of energy is a very small fraction of the total one, since the energy other than solar is generally required for operating pumps and controls. Thus, the major share of the water cost in solar distillation is that of amortization of the capital cost. The production rate is proportional to the area of the solar still, which means the cost per unit of water produced is nearly the same regardless of the size of the installation. This is in contrast with conditions for fresh water supplies as well as for most other desalination methods, where the capital cost of equipment per unit of capacity decreases as the capacity increases.

This means that solar distillation may be more attractive than other methods for small sizes. Howe and Tleimat (1974) reported that the solar distillation plants having capacity less than 200 m^2/day are more economical than other plants.

Kudish and Gale (1986) have presented the economic analysis of solar distillation plant in Israel assuming the maintenance cost of the system to be constant. An economic analysis for basin and multiple-wick type solar stills has been carried out by various scientists (Delyannis and Delyannis, 1985; Tiwari and Yadav, 1985; Mukherjee and Tiwari, 1986; Yadav and Tiwari, 1987). They have done economic analysis by incorporating the effect of subsidy, rainfall, salvage value and maintenance cost of the system. Barrera (1992) had developed a solar water still called staircase solar still in Mexico and presented a techno-economic analysis for the same. He stated that distilled water production for potable use might be 3.5 times more economical than chemical water acquisition.

Zein and Al-Dallal (1984) performed chemical analysis to find out its possible use as potable water and results were compared with tap water. They concluded that the condensed water can be mixed with well water to produce potable water and quantity of this water is comparable with that of obtained from industrial distillation plants. Further the tests performed showed that impurities like nitrates, chlorides, iron, and dissolved solids in the water are completely removed by the solar still.

The pay back period n_p can be obtained as

NP = [log(UA/(UA - i x PÞÞ= logð1 þ i)] (9)

where P and i are initial cost and the rate of interest respectively and UA is unacost (Tiwari, 2002). If payback period is less than the life of solar still, the investment is advisable otherwise not.

9. Conclusions and recommendations

On the basis of discussion in various sections, the following conclusions and recommendations can be inferred:

(a) The double slope FRP conventional solar still is the most economical solar still to provide drinking water for domestic applications at decentralized level. This is due to the fact that it is simple in design and fabrication, easy to handle (unskilled manpower is sufficient) along with longer life, low unacost and low cost of water per litre. Further, due to low operation and maintenance cost it is most suitable in rural areas of remote region.
(b) The active solar still is more suitable for commercial applications like distilled water for selling purposes, extraction of essence from different seeds and green leaves etc., use in batteries, chemical laboratories etc.
(c) For every new design at different operating temperature ranges, the values of C and n should be calculated for actual field conditions to know internal heat transfer for realistic performance estimations and projections.

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