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Analytical expression for instantaneous exergy efficiency of a shallow basin passive solar still

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A R T I C L E I N F O

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A B S T R A C T

An expression for instantaneous exergy efficiency of a passive solar still has been developed. The effect of design, operational and climatic parameters, namely effective absorptivity of basin liner (0.9–0.6), glass cover tilt (15–45°) and wind velocity (0.0–10 m/s) have been taken into account. It is found that with decrease in absorptivity (0.9–0.6) with time, the energetic and exergetic efficiencies decrease by 21.8% and 36.7% respectively. The effect of glass cover tilt is found to be insignificant and the respective efficiencies decrease by 0.75% and 0.47% per degree increase in tilt. These efficiencies increase rapidly up to a wind velocity of 2 m/s.

1. Introduction

The demand for good quality drinking water is increasing steadily and it is a major problem in many developing countries. One of the promising options for eliminating the major operating cost of distillation plant is direct use of solar energy. The solar distillation is a technique to produce potable water at lower cost than the other available desalination processes for a certain amount of water produced (demand is less than 200 m^3/day [1]). It is one of the technologies with better solution to the problem of energy security and climatic change with almost negligible running cost. The passive solar still is one of the conventional designs in use, since 1842 (built in Chile in 4000 m^2 area). Like other thermal systems, it needs to design the passive solar still by using the concept of efficiency. Bejan [2] reviewed the work on solar thermal systems according to the laws of thermodynamics. Singh and Tiwari [3] derived an analytical expression for the thermal efficiency of the passive solar still in terms of system design and climatic parameters after incorporating an effect of water flow over the glass cover and using temperature dependent internal heat transfer coefficient. Tiwari and Noor [4] presented the concept of instantaneous energy efficiency to characterize the design of solar stills.

Various researchers have proved that, in addition to the first law, the design of thermodynamically efficient heat transfer system must be based on the second law of thermodynamics. Cornelissen [5] has given in detail the numerous methods of formulating exergetic efficiency for various energy systems. For the thermal systems, which use solar energy, the exergy transfer takes place with mass flow and heat interaction. Dincer [6] highlighted the importance of exergy and its essential utilization in numerous ways. He has reported the linkages between energy and exergy, exergy and environment, energy and sustainable development and energy policy making and exergy. In recent years an exergy analysis has proven to be a powerful tool in the simulation of thermodynamic analysis of energy systems. It has been widely used in the design, simulation and performance evaluation of energy systems. Rosen and Dincer [7] have reported that exergy analysis can be used for possible thermodynamic improvement of the process under consideration. To state exergetic efficiency of system, DiPippo [8] has presented two different approaches, namely Brute-force exergy efficiency and Functional exergy efficiency.

Dodge [9] has obtained a relation for minimum work (exergy) to extract pure water from salty solution. In the field of solar distillation, Garcia-Rodriguez and Gomez-Camacho [10] have evaluated the performance of the solar desalination system 'Sol-14', using energy and exergy analysis in order to propose possible improvements in the system. A typical ideal distillation process with the aim of minimum work requirement has been proposed and analyzed by Cerci [11].

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Sow et al. [12] have carried out the exergy analysis to define the thermodynamic efficiency correctly, expressing the degree of perfection. They reported the exergetic efficiencies in the range of 19–26% for triple effect system, 17–20% for double effect system, and less than 4% for single effect system. Hepbasli [13] has done a key review on exergetic analysis and assessment of various renewable energy resources (i.e. solar collector, solar cooker, solar drying, solar desalination, solar thermal power plants, and hybrid PV thermal solar collector) for sustainable future. Torchia-Nunez et al. [14] have carried out theoretical exergy analysis of the shallow passive solar still for 0.01 m water depth using approach of irreversibility in various components and reported that for same exergy input a basin liner, brine and solar still have exergy efficiencies of 12.9%, 6% and 5%, respectively.

It has been reported that for maximum annual yield from the solar still depends on latitude and glass cover tilt angle [15]. Also an effective absorptivity of basin liner decreases with time, due to deterioration of absorber liner if not maintained. Therefore, the following investigations are made in the present study.

- To develop an expression for instantaneous exergy efficiency of the passive solar still in terms of design and climatic parameters.
- To study the effect of various parameters namely effective absorptivity, glass cover tilt, water depths, and wind velocity on instantaneous energy and exergy efficiency.
- To analyze the relative influence of water temperature on the fractional exergies within the solar still.

2. Description of solar still

The schematic of the passive solar still is shown in Fig. 1. It shows the various components of energy balance and thermal energy loss in a conventional single slope solar still. The still consists of an air tight basin, usually constructed out of concrete/cement, galvanized iron sheet (GI), galvanized reinforced plastic (GRP) or fibre reinforced plastic (FRP) of better insulating materials. The FRP basin of area of 1 × 1 m size, 0.005 m thickness, and thermal conductivity of 0.35 W m^{-1} K^{-1} has been considered in the analysis. The basin liner is painted black to increase its absorptivity to radiation. The transparent glass cover of thickness 0.004 m and thermal conductivity of 0.76 W m^{-1} K^{-1} is fixed on the top at an inclination, which allows 95% the solar radiation (short wave) to transmit inside, which mostly absorb by the blackened absorber liner and water in it. Upon striking a blackened surface, the basin liner also radiates energy in the infra-red region (long wavelength), which is reflected back into the still by top glass cover, trapping the solar energy inside the still and producing the greenhouse effect. The rubber gasket is placed between the glass and the top frame of basin to avoid vapour leakage to outside. The cover is further sealed externally using window putty around the setting. As the water heats up, it begins to evaporate. The pure vapour rises towards a cooler area (i.e. glass) and almost all impurities are left behind in the basin. There is a provision to collect distillate output at the lower ends of top cover. The evaporated water from the water surface gets condensed on the inner surface of the glass cover. The condensed water is trickled down and collected in a trough fixed at the lower side wall of the basin. The known quantity of brackish water can be filled up in the solar still through feed valve provided. The stills require frequent flushing, which is usually done during the night. Flushing is performed to prevent salt/silt precipitation.

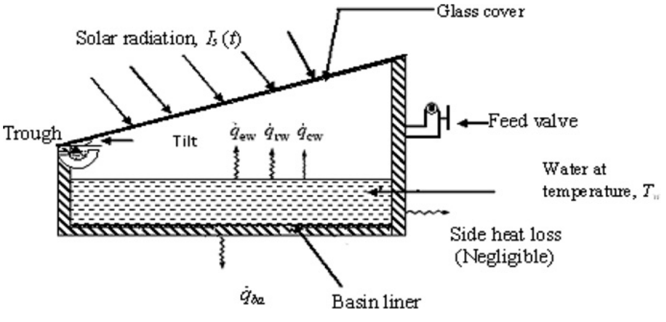

Fig. 1. Thermal energy losses in different components of the solar still.

Design problems encounter with solar stills are vapour tightness of the enclosure, distillate leakage, methods of thermal insulation, and cover slope, shape and material. The corrosion conditions at the basin liner can be so severe that basins made of metal – even those coated with anti-corrosive materials – tend to corrode. It is required for glazing material to be strong enough to resist high winds, rain, hail, and small earth movements. Other factors determining the suitability of glazing material include the cost of the material, its weight, life expectancy, local availability, maximum temperature tolerance, and impact resistance, as well as its ability to transmit solar energy.

3. Analysis

The following assumptions have been made during analysis to derive an expression.

- The solar still is vapour tight and operates in quasi steady state,
- The absorptivity (α'_g) and thermal resistance of the glass cover is negligible,
- Heat capacity of the glass and material of the solar still is negligible,
- There is no thermal stratification across the water depth,
- The side heat loss from the basin is negligible,
- Heat transfer coefficients are temperature dependent.

3.1. Analytical expression

The exergy associated with heat interaction that is not radiation, can be expressed as [16];

$$\dot{E}x = \dot{q}_u\left(1 - \frac{T_a}{T}\right) \tag{1}$$

where $\dot{q}_u$ and $\dot{E}x$ are the useful energy and exergy flux associated with the system at temperature, T.

The exergy efficiency of the solar still can be defined as the ratio of exergy output associated with the product (i.e. distillate yield) to the exergy input (radiation exergy), and can be expressed as [8];

$$\varepsilon = \frac{\text{Exergy output from passive solar still}}{\text{Exergy input to passive solar still}} = \frac{\dot{E}x_{\text{out}}}{\dot{E}x_{\text{in}}} = \frac{\dot{E}x_{\text{evaporation}}}{\dot{E}x_{\text{sun}}} \tag{2}$$

The maximum efficiency ratio (exergy-to-energy ratio for radiation) for evaluating exergy of the solar radiation at temperature T_s is expressed [17] as follows;

$$\frac{\dot{E}x_{\text{in}}}{I_{s,\text{in}}(t)} = \frac{\dot{E}x_{\text{sun}}}{I_{s,\text{sun}}(t)} = \left[1 - \frac{4}{3}\times\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\times\left(\frac{T_a}{T_s}\right)^4\right] \tag{3}$$