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Design, fabrication and performance of a hybrid photovoltaic/thermal (PV/T) active solar still

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ABSTRACT

Two solar stills (single slope passive and single slope photovoltaic/thermal (PV/T) active solar still) were fabricated and tested at solar energy park, IIT New Delhi (India) for composite climate. Photovoltaic operated DC water pump was used between solar still and photovoltaic (PV) integrated flat plate collector to re-circulate the water through the collectors and transfer it to the solar still. The newly designed hybrid (PV/T) active solar still is self-sustainable and can be used in remote areas, need to transport distilled water from a distance and not connected to grid, but blessed with ample solar energy. Experiments were performed for 0.05, 0.10, and 0.15 m water depth, round the year 2006–2007 for both the stills. It has been observed that maximum daily yield of 2.26 kg and 7.22 kg were obtained from passive and hybrid active solar still, respectively at 0.05 m water depth. The daily yield from hybrid active solar still is around 3.2 and 5.5 times higher than the passive solar still in summer and winter month, respectively. The study has shown that this design of the hybrid active solar still also provides higher electrical and overall thermal efficiency, which is about 20% higher than the passive solar still.

1. Introduction

All ecosystems and every field of human activity depend on clean water and it is one of the most precious earth's resources in today's world. Water is a primary need of life, health, and sanitation and is the most important issue in the international agenda. Water resources around the world are under pressure. The world's supply of fresh water is running off because of increasing demand due to increasing population, industrialization, and draught at various locations, followed by desertification. Water available in rivers, lakes, and underground reservoirs is being polluted due to industrial, agricultural and population growth during the current years. The global consumption of water is doubling in every 20 years, more than twice the growth rate of human population as estimated. According to the United Nations, more than one billion people already lack access to fresh drinking water. The present fresh water resources, which are less than 1%, are inadequate to support life and vegetation on the earth and will not be able to meet the requirements in future. If current trends persist, by 2025 the demand for fresh water is expected to rise by 56% more than the amount of water that is currently available.

Decline in drinking water quality is affecting millions in developing countries. Many developing countries including India have given utmost priority to rural water supply in their development plans. At present India has 16% of world population but only 4% of its fresh water supplies. To distillate the saline/brackish water to fresh water for human consumption and for other utility, different technologies has been used for about century and the use of distillation technology has been accelerated after world war-II. Many options (conventional and non-conventional) are available to distillate the brackish/saline water. Among the non-conventional methods, to disinfect the polluted water, the most prominent method is the 'solar distillation' to get the potable/distilled water by utilizing the solar energy and has been practiced for centuries. Comparatively this requires simple technology, eco-friendly, lower maintenance and no energy costs, due to which it can be used anywhere with lesser number of problems. However, these advantages of simple passive solar stills are off set because of low yield, approximately 2–3 L/m^2 day, low efficiency and dependent on solar intensity, which varies with location.

Broadly, solar distillation systems are classified as passive and active solar stills and various scientists throughout the world have carried out numerous research works on design, fabrication methods, testing and performance evaluation, etc. as historically reviewed by Tiwari et al. [1]. Cooper [2] reviewed the factors affecting the absorption using shallow basin passive solar still. An ideal solar still has been proposed to attain maximum ideal efficiency of 60% over a day's operation. However, maximum experimental efficiency for solar still operating near to ideal (cover

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Nomenclature

A_c	area of collector (m^2)
A_m	area of PV module (m^2)
A_s	area of solar still (m^2)
$I_c\ (t)$	total solar intensity on the glass covers of collector panel (W/m^2)
$I_m\ (t)$	total solar intensity on the glass covers of PV module (W/m^2)
$I_s\ (t)$	total solar intensity on the glass covers of solar still (W/m^2)
$I_{c,d}\ (t)$	instant diffuse solar intensity on the glass covers of collector panel (W/m^2)
$I_{s,d}\ (t)$	instant diffuse solar intensity on the glass covers of solar still (W/m^2)
I_{SC}	short circuit current (A)
I_L	load current (A)
T_b	basin temperature (°C)
L	latent heat of vaporization (J/kg)
$\dot{m}_{ew}$	distillate yields (kg/m^2 h)
T_{go}	glass outer surface temperature (°C)
T_{gi}	glass inner surface temperature (°C)
T_v	vapor temperature (°C)
V_a	wind velocity (m/s)
V_{OC}	open circuit voltage (V)
V_L	load voltage (V)

Greek symbols

η_e	electrical efficiency
η_{eth}	equivalent thermal efficiency
η_{th}	thermal efficiency
η_o	overall thermal efficiency

inclination 10° and 0.0095 m water depth) rarely exceeds over 50%, as predicted. Gomkale and Datta [3] designed a simple double-sloped solar still using aluminum components and black polyethylene film as the base liner and insulation bed of sand and sawdust at the bottom using wooden basin. They predicted annual average productivity of 2.51 L/m^2 day, i.e. an efficiency of 28% at Bhavnagar (India). Garg and Mann [4] reported that the distillate output from the solar stills depend on climatic conditions, thermo physical properties of construction material, its orientation, cover tilt angle, water depth, vapor leakage and operating parameters. They reported 26% heat loss through the base of solar stills and recommended insulated base to lower down the loss. Al-Hinai et al. [5] studied the effect of effect of climatic, design and operational parameters on the yield of a simple solar still. They recommended optimum thickness of insulation as 0.1 m, under the Omani climatic conditions, after which the increase in the still yield does not justify the additional insulation cost. They have also recommended the brine water depth in the range of 0.02–0.06 m for better yield and found an increase in daily yield by 8.2% with rise in ambient temperature from 23 to 33 °C. Malik et al. [6] included importance, history and background of solar distillation and predicted maximum efficiency of 30% for passive solar still. Fath et al. [7] designed the pyramid shaped passive solar still and found that average daily annual productivity from both pyramid and single slope solar still was nearly same and close to 2.6 L/m^2 day.

El-Sebaii [8] selected different designs of the passive and active solar stills to study the effect of wind velocity, water and glass cover temperatures, and water depth on the yield. The single slope single basin still with water flowing in the basin and the vertical solar still were selected as an active solar still. He reported that daily yield of the active basin type, wick-type and vertical solar stills increase as wind velocity increases up to the typical velocity, possibly because their overnight yields equal zero. However, for single effect passive stills, there is a critical depth (0.05 m) beyond which the yield increases with increase in wind velocity. Boukar and Harmim [9] reported that daily yield from simple double basin solar still increases nearly two times after coupling it to a flat plate collector during clear days in summer.

The simple basin solar still has several advantages over other known desalination methods. It is simple in construction, direct use of free solar energy, minimal need for maintenance, self-operation and long lifetime, but the low yield offsets these advantages. The yield can be increased by feeding the hot water in the basin and to achieve so, the different designs of active solar distillation systems have been proposed by various researchers. Singh and Tiwari [10] evaluated the monthly performance of passive and active solar stills for different Indian climatic conditions for different water depths and reported that the yield significantly depends on water depth and annually maximum for glass cover inclination equal to the latitude of the place. Voropoulos et al. [11] reported that by coupling of the solar still with thermal storage, heated by flat plat collectors, the yield increased by two times than that of the solar still only. Zaki [12] carried out experimental investigation on an active system under thermosyphon mode of operation and reported that the maximum increase of yield by 33%, when the water in the single slope solar still was preheated in the flat plate collector. Recently, Tiwari et al. [13] developed a thermal model for integrated active solar still coupled with different types of the solar collectors and validated with experimental values for 0.05 m water depth. They concluded that active solar still integrated with evacuated tube collector with heat pipe gives yield 4.24 kg/m^2 day, maximum among all other type of solar still. The yield in these active methods of solar distillation has been increased significantly, but operation depends on power supply and if PV operated, the thermal energy of solar cells convected from back surface was not utilized usefully.

Once thermal energy withdrawal is associated with the photovoltaic (PV) module, it is referred as hybrid (PV/T) system. The concept behind the hybrid is that a solar cell converts solar radiation to electrical energy with peak efficiency in the range of 9–12%, depending on specific solar-cell type and thermal energy dissipated for air or water heating. More than 80% of the solar radiation falling on photovoltaic (PV) cells either reflected or converted to thermal energy. In view of this, hybrid photovoltaic/thermal (PV/T) collectors are introduced to simultaneous generate electricity and thermal power, Je et al. [14]. Fujisawa and Tani [15] have done the annual exergy based evaluation of hybrid photovoltaic/thermal (PV/T) collector. They predicted the higher output density from the system than in a unit PV module or in a liquid flat plate collector. Hung et al. [16] have studied the experimental performance of unglazed PV integrated solar collector for water heating under natural mode and found primary energy saving efficiency exceeds 60%, which was higher than for a conventional solar water heater or pure PV system.

Chow [17] has analyzed the performance of PV/T water collector with single glazing in transient conditions, including the instantaneous thermal/electrical gains efficiencies, and thermal state of various collector components. He reported an increase of electric efficiency by 2% at mass flow rate of 0.01 kg/s and reported 60% thermal efficiency of the system. Later, Chow et al. [18] have concluded that the tube-in-plate absorber collector with single glazing regard as one of the most promising design. They have ob-