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Productivity correlation and economic analysis of floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery

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ABSTRACT

In this study, experiments were performed with floating wick basin type vertical multiple effect diffusion solar still with waste heat recovery (FW-BVMED-HR) by varying several design and operational parameters. The FW-BVMED-HR still had floating wicks in the basin and a heat exchanger for waste heat recovery. The experimental database of present study was used to develop productivity correlation to predict the productivity of FW-BVMED-HR still. The productivity correlation has been further used for economic analysis of FW-BVMED-HR still, based on life cycle costing of the system. The capital cost of this still with increasing number of effects, from 2 to 7, is computed. The annual cost of operating this still based on a life cycle of 10 and 25 years is estimated. The average annual distillate and minimum unit cost of distillate, for increasing number of effects is determined. The minimum cost of distillate obtained for the 7 effect FW-BVMED-HR solar still is estimated to be Rs. 5.45/kg, for a life cycle of 25 years and for interest rate 0.16. With lower interest rate of 0.12, the cost of distillate reduces significantly to Rs. 4.52/kg. The still is found to be economically viable with low payback period.

1. Introduction

Solar distillation technology is both technically and commercially viable today and, hence, it has become an attractive option for areas of the world which are facing shortage of safe drinking water. However for it to be cost competitive, efforts are needed to upgrade the existing technology in order to reduce the unit cost of generating water. The design and operational parameters of the solar still should be optimized to obtain minimum cost of distillate per kg.

The productivity of single effect basin still can be significantly increased by utilizing the input heat energy several times in multiple effect diffusion still [1–17]. The multiple effect diffusion still consists of multiple partition plates which are arranged parallel to each other with a narrow gap between the partition plates. One side of each of the partition plates is covered with porous wick cloth, having low thermal inertia. Heat is supplied to one side of the multiple partition plate arrangement and feed water is fed continuously to each of the wick sides of the partition plates. As heat is supplied to the first partition plate, water vapors generate from the wick side of the first partition plate, diffuse through the air gap between the partition plates and condense on the uncovered surface of the second partition plate. The latent heat released by condensing vapors conducts through the partition plate and further evaporates the water from the wick side of the second partition plate. In this way, the heat energy supplied to the first partition plate can be recycled several times to increase the productivity of the still. Tanaka et al. [1] obtained distillate productivity of 14.8–18.7 kg/m^2/day for basin type vertical multiple effect diffusion solar still, at daily solar radiation of 20.7–22.4 MJ/m^2/day and ambient temperature ranging from 19 to 30 °C, when 11 number of partition plates were used at 5 mm partition gap. From experiments done on vertical multiple effect diffusion solar still coupled with flat plate reflector Tanaka [2] obtained a distillate productivity of 13.3 kg/m^2/day for a 6 effect still at 5 mm partition plate gap, at daily solar radiation of 20.2–22.9 MJ/m^2/day on glass cover, which is nearly 5.5 times the distillate productivity of a basin type still. Tanaka et al. [5] estimated from numerical simulation that the basin type vertical multiple effect diffusion solar still with 10 distillation cells having 5 mm partition gaps, utilizes the solar radiation incident on the glass cover 3.5 times more effectively than the single slope basin type still.

Parametric study of various types of multi-effect diffusion solar stills – horizontal, inclined and vertical has been done numerically and experimentally by researchers to find the effect of various parameters on the productivity and efficiency [3,6,8,11,18–22]. As the number of effects increase, the productivity of the multi-effect diffusion still also increases [6,8,11,19]. Tanaka et al. [6] in a parametric study by numerical simulation found that the productivity of a basin type vertical

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multiple effect diffusion solar still with 13 partitions at 5 mm partition gaps was about 4 times the productivity of a basin type still. Minimizing the diffusion gap between partition plates not only helps in a compact design but also increases the productivity of the multi-effect diffusion stills [6,8,11,18,22]. The efficiency and productivity of the multi-effect diffusion still decreases with increase of feed water rate to the wicks of the partition plates [3,6,11,18,19]. With the increase of feed water temperature, the efficiency and productivity of a multi-effect diffusion still increases [8,20,21]. With increase of solar radiation, the efficiency and productivity of the multi-effect diffusion still increases [2,20]. An optimum size basin tank must be designed from cost considerations and optimum operational efficiency [23]. Adhikari and Kumar [24] carried out an economic analysis, of multi-staged stacked tray solar still coupled with flat plate collector, based on life cycle costing of the system. As the number of stages increases the unit cost of distillate C_u shows a variation of parabolic shaped curve i.e. it first decreases and then increases with increase of number of stages. The optimum number of stages were found to be 3. The unit cost of distillate C_u decreases when the flat plate collector area is increased. Kumar and Tiwari [23] compared the cost of distillate from passive single slope basin still with that obtained from hybrid photovoltaic-thermal active solar still, based on life cycle costing of systems. They found the annual yield and cost of distilled water obtained from the hybrid photovoltaic-thermal active solar still to be 3.5 and 2.8 times respectively, than that obtained from passive single slope basin still. Rahbar and Esfahani [25] studied a new design of portable thermoelectric solar still utilizing heat pipe. They compared the per liter generation cost of distillate of this still with that obtained from other solar stills. The unit cost of distillate for their still was found to be 0.18 $/l/m^2 as against 0.035 $/l/m^2 for the single slope basin still. Khayet [26] carried out an extensive literature survey of the specific energy consumption and unit distillate cost of membrane distillation, and compared them with other desalination processes. He reported that of all desalination technologies, Reverse osmosis is very cost competitive, with unit distillate cost of $0.55/m^3 for 30 m gallons/day capacity system. However, the unit cost of distillate C_u for small scale plants is on considerably higher side and non-competitive for some of these technologies. Kabeel et al. [27] have estimated the unit cost of distillate for 17 different design configurations of solar stills available in literature. Annual productivity, annual maintenance operational cost, annual salvage values, life cycles of stills were considered for estimating the annual cost and unit cost of distillate for these stills. They found that unit cost of distillate was minimum for the pyramid shaped solar still and it was 0.03 $/l which was estimated from numerical computation with assumption of year round operation.

The solar stills use solar energy which has no cost and also it is clean energy and renewable energy without any environmental hazard. All other technologies used for distillation of water utilize either electrical energy or fossil fuel energy both of which cause environmental hazards also. Moreover, they are not cost-free and many a times are in short supply due to industrial and household demand for them. The solar distillation technology is very attractive option for desert and remote areas where conventional sources of energy are not available. Other desalination technologies may need water pre-treatment before feeding to the distillation unit. The solar distillation technology has no pre-requisites for input feed water quality (chemical, TDS etc.) except simple mechanical filtration. Hence for obtaining safe drinking water for small household units in desert and remote areas, solar distillation units are very attractive alternatives. Other technologies are capital intensive for small scale plants and not affordable by small households in remote areas. The unit cost of distillate C_u for small scale plants is high and non-competitive for some of the other desalination technologies [26].

In the present work, the conventional design of basin type vertical multiple effect diffusion (VMED) solar still has been modified by incorporating improvements like floating wick in the basin and heat exchanger for waste heat recovery. The multiple floating wicks were placed in basin to reduce thermal inertia of evaporating surface [28] and a heat exchanger was used to preheat the feed water by recovering heat from hot waste feed water leaving from the bottom of wick covered side of vertical plates. This modified still is referred to as FW-BVMED-HR (floating wick basin type vertical multiple effect diffusion solar still with heat recovery) solar still in this paper. Recently, the authors of the present work, have reported results from experiments conducted on four effect FW-BVMED-HR solar still [17]. They found that the distillate productivity of FW-BVMED-HR still was 21% higher than the reference still on a clear sunny day. The objective of this work is to propose a productivity correlation which can predict the productivity of FW-BVMED-HR still with reasonable accuracy. The principle weather parameters such as daily total insolation and daily average ambient temperature, along with important operational and design parameters such as feed water rate, feed water temperature, number of effects and gap between partition plates, are taken into consideration for the development of correlation. Such productivity correlation can be useful in estimating the productivity to carry out techno-commercial feasibility studies before installation of similar type of solar distillation unit in any part of the world. The other objective of the present work is to find the minimum unit cost of distillate for the FW-BVMED-HR still, based on the life cycle costing method. The capital cost of this still with increasing number of effects, from 2 to 7, is computed. The annual cost of operating this still based on a life cycle of 10 and 25 years is estimated. The effect of varying the rate of interest, on the unit cost of distillate, is also studied, for interest rates 0.12 and 0.16. The average annual distillate and unit cost of distillate, for increasing number of effects is evaluated. Furthermore, the capital cost of the still is expected to come down by 10% due to procurement of raw material at lower prices on account of bulk order of materials, for mass production of still. Hence, the unit cost of distillate is also computed with the assumption of reduction of 10% on the capital cost of the still. Payback periods for various conditions is also computed.

2. Experimental set up and procedure

Figs. 1 and 2 show the photographic view and schematic diagram of FW-BVMED-HR still used in the present study. The development and dimensional details of various components of still are already provided

Fig. 1. Photographic view of FW-BVMED – HR solar still.