Cost optimization studies on a multi-stage stacked tray solar still

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Abstract

In the present paper a techno-economic analysis of a multi-stage stacked tray (MSST) solar still coupled with a solar collector has been developed. The thermal model developed earlier by the authors for predicting the system performance has been used here also; the model considers transient heat and mass transfer processes within the solar still. The economic analysis is based on the life-cycle costing of the system, taking into account the capital and maintenance costs of the system for estimating the cost of unit mass of distilled water. The techno-economic analysis presented shows that the system parameters need to be optimized, resulting in the minimum cost of distilled water. As an illustration, results of numerical calculations for the climate of Delhi, India, are presented in the paper.

Keywords: Solar still; Multi-stage distillation; Cost optimization; Techno-economics

1. Introduction

The non-availability of pure water presents a serious problem in many parts of the world. One of the important causes of water impurities is the salinity ingress, which normally influences the areas along the sea coast or the creeks carrying high tidal waters over 2–25 km inland. Some pockets, in the areas far away from coastal plains, have also seen the aquifers available there affected by salinity. It is estimated that a sizable population in India and also in the world, both urban and rural, has no access to pure water and hence has been drinking water for generations with TDS around 1500–2000 mg/l. In India about 53,000 habitations, mostly remote and arid, are estimated to have salinity greater than 1500 mg/l. 

Apart from salinity, another important problem affecting water quality is its brackish
nature. In India alone, about 28% of the total number of villages have been identified as having such a problem, which gets further complicated with scarcity and contamination of water. In this scenario, renewable energy-based desalination systems, particularly those operated by solar energy, offer a viable option to produce fresh water, especially where the locations are scattered and the demand for pure water is not very high. Fortunately, a very good number of Indian locations lie in high radiation zones where the annual averaged daily solar radiation on a horizontal surface is in the range of 5.4 to 6.4 kWh/m² (Fig. 1) as estimated in [1].

Solar distillation has been studied in the literature in great detail and many installations have been erected based on the basin-type configuration of solar stills [2]. The basin-type configuration, however, produces small quantities of distillate output corresponding to a unit area of solar radiation collection. A number of efforts have been made to develop more efficient designs so as to produce a higher level of output from the same collector area. One of the configurations, a multi-stage stacked tray (MSST) solar still, has shown high potential during testing of prototype models for producing enhanced distillate output [3–7], as the design provides an effective way of reutilizing latent heat of condensation. The total distillate output from the MSST solar still increases when the number of stages is increased; the fractional increase, however, is found to be lower for each of the added stages. Contrarily, the cost of the distillation system increases linearly when new stages are added. This trend indicates that the addition of new stages may not be advantageous after a certain number depending upon various design and cost parameters, and therefore calls for optimization.

In this paper, a techno-economic model is presented to facilitate optimization of the design parameters of a MSST solar still coupled with a solar collector. The cost of unit mass of distilled water has been taken as an optimization parameter. The thermal model used for predicting the performance of the system considers transient heat and mass transfer processes within the solar still. The economic analysis is based on the life-cycle costing of the system, which takes into account the capital and maintenance costs for estimating the cost of unit mass of distilled water. As an illustration, results of numerical calculations for the climate of Delhi, India, are presented herein. The results have also been presented to show a comparative economic performance of the MSST solar still vis-a-vis conventional single-basin solar stills.

2. System description

The MSST solar still consists of a distillation chamber and a solar collector, both coupled
Fig. 2. Schematic configuration of a multi-stage stacked tray solar still coupled with a solar collector through heat exchanger.

together through a heat exchanger. Schematics of the system are shown in Fig. 2. The distillation chamber consists of various metallic trays, stacked one upon another in an air tight fashion. Solar radiation is collected and converted to heat by the solar collector; the heat, when supplied to the distillation chamber, results in an increase of water temperature, thereby enhancing the rate of evaporation. When water vapour reaches equilibrium with the tray in next stage, condensation occurs. The trays, therefore, are designed with two sides sloped at the bottom so that the water vapour condensed on this surface slides down to the collection troughs fitted at the sides. The latent heat released during the condensation process heats the water in the next tray, and the process of evaporation and condensation also occurs there in a similar fashion. The last tray is kept shaded to avoid absorption of solar radiation, but a provision is ensured that there is free movement of air. The whole distillation chamber is insulated on all sides to prevent heat losses from the water to the outside environment.

3. Mathematical analysis

A computer simulation model has been developed by the authors [6] to predict thermal performance of a MSST solar still coupled with a solar collector. The model considers detailed energy balance equations for various components of the system, viz. water mass and metallic trays in different stages, a solar collector, and heat exchanger through which the coupling is made between the distillation chamber and solar collector. The model assumes that:

- an equilibrium is reached in every stage between the water surface and air, and air and condensing surface
- the solar collector is operating in the thermosyphon mode
- the connecting pipes are well insulated and
therefore the heat losses through them are negligible
• the thermo-physical properties of water and air remain constant.

The model outputs water temperature in different stages along with an estimate of distillate output from each of the stages. The daily distillate output may be evaluated by the following expression:

\[
M_d = \sum_{i=1}^{N} \int_{t=1}^{24} M_{e,i} dt
\]  

(1)

The annual average distillate output is estimated as follows:

\[
M_y = \left[ \sum_{m=1}^{12} M_{d,xN_{d,m}} \right] \left( \frac{1}{365} \right)
\]  

(2)

In order to evaluate economic performance of the system, a life-cycle costing is done whereby the annual cost of the total system including solar collector and heat exchanger is given by the following expression:

\[
C_r = C_s f_S + C_{c,e} f_c + C_{h} f_h + M_s f_s + M_e f_e + M_h f_h
\]

\[+ M_{c,s} f_{c,s} + S_{c,e} f_{c,e} + S_{h} f_{h}
\]

(3)

where the factors \(C\) represent the capital cost of various components, \(M\) the cost of preventive maintenance represented as fraction of capital cost of a particular component, \(f\) the capital recovery factors, and \(F\) the sinking fund factors.

The cost of unit mass of distilled water can be evaluated dividing the annual cost of the system [represented by Eq. (3)] by annual distillate production [given by Eq. (2)], i.e.,

\[
C_u = \frac{C_r}{M_y}
\]

(4)

4. Numerical results and discussion

In order to appreciate the developed techno-economic model for optimization of system parameters of a MSST solar still, numerical calculations were made corresponding to the climatic data of Delhi, India. Annual average daily distillate output of a MSST solar still for various \(R\) values is shown in Fig. 3 where \(R\) represents the ratio of solar collector area to the base area of distillation chamber. The figure illustrates that \(M_y\) increases as the area of solar collectors is increased. The effect is more pronounced for systems with a higher number of stages. The fractional increase in the distillate output, however, may be seen to be decreasing as the area of solar collectors is increased. This

![Graph showing variation of yearly average distillate output](image)

Fig. 3. Variation of yearly average distillate output of a MSST solar still as a function of number of stages for different values of the solar collector area represented by \(R\).
Fig. 4. Variation of $C_u$ as a function of the number of stages for different values of a solar collector area represented by $R$.

Strongly indicates the need for economic optimization, as an increase in the cost of the system on account of an increased solar collector area does not seem to correspond to the matching benefit in respect of enhanced distillate output. This needs to be done taking into account the climatic data of the location and corresponding cost parameters.

Fig. 4 presents the results of calculation in respect of the cost of unit mass of distilled water obtained from a MSST solar still coupled with a solar collector as a function of $R$ and number of stages. It may be noted here that the present system is still in the R&D stage, and therefore the costs of various components are estimated based on (1) the requirement of metal sheet for fabrication; (2) the requirement of various other associated materials viz. gasket, clamps, adhesives, insulation, cladding, etc., and (3) the requirement of skilled and semi-skilled labour.

The cost of solar collectors is directly taken from the market, as there is a large industrial base available in India for manufacturing of solar collectors. The cost figures also include an appropriate amount in respect of the profit margin and overhead costs of a company in a small scale sector in India. The collector design and its costs are fairly standardized, and typical values have been used in the calculations. The various other parameters related to the cost calculations are given in Table 1. It is clearly seen from Fig. 4 that the value of $C_u$ falls to a certain point, and thereafter starts increasing. The stage where the minimum occurs for the value of $C_u$ represents the optimum number of stages. Similarly, the numerical calculations can be extended to evaluate the optimum value of the solar collector area corresponding to the minimum value of $C_u$.

It may be noted here that the present study has used copper as the material of construction for the distillation chamber; however, the calculations can also be made in a similar fashion for other materials (such as stainless steel).

Numerical calculations have also been made to carry out a comparative performance analysis of a MSST solar still with a conventional single-basin solar still (SBSS). Fig. 5 shows the
Table 1
Cost analysis parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material costs:</td>
<td></td>
</tr>
<tr>
<td>Copper (0.56 mm), Rs/kg</td>
<td>160.0</td>
</tr>
<tr>
<td>Insulation (50 mm thick glass wool), Rs/m²</td>
<td>100.0</td>
</tr>
<tr>
<td>Solar collector (copper–copper, selectively coated), Rs/m²</td>
<td>4000.0</td>
</tr>
<tr>
<td>Heat exchanger (copper), Rs/m²</td>
<td>180.0</td>
</tr>
<tr>
<td>Other, % of costs of metal plus insulation</td>
<td>3</td>
</tr>
<tr>
<td>Cost of labour, % of the costs of metal sheet plus insulation</td>
<td>15</td>
</tr>
<tr>
<td>Overhead cost, % of the costs of metal sheet plus insulation</td>
<td>20</td>
</tr>
<tr>
<td>Maintenance costs:</td>
<td></td>
</tr>
<tr>
<td>Solar collector, % of its cost</td>
<td>3</td>
</tr>
<tr>
<td>Distillation chamber, % of its cost</td>
<td>3</td>
</tr>
<tr>
<td>Life of the system, y</td>
<td>10</td>
</tr>
<tr>
<td>Salvage value, % of its cost</td>
<td></td>
</tr>
<tr>
<td>Solar collector</td>
<td>10</td>
</tr>
<tr>
<td>Distillation chamber</td>
<td>10</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>15</td>
</tr>
<tr>
<td>Net rate of interest discounting for rate of inflation, %</td>
<td>12</td>
</tr>
</tbody>
</table>

variation of $C_u$ as a function of the solar absorber area for a MSST solar still with three and six stages, and for a single-basin solar still for which it is also assumed that the absorption of the basin liner remains at a level of 60% with regular maintenance. The value of $C_u$ is seen constant for the latter case, as the system cost is assumed to increase linearly with an increase in the solar absorber area. It is obvious that the value of $C_u$ becomes quite competitive when higher values of the solar absorber area are used in a MSST solar still.

Fig. 5. Comparative performance of a MSST solar still with $N=3$ and 6 and a conventional single-basin solar still for different values of the solar collector area.

5. Symbols

$C_{c}, C_{h}, C_{S}$ — Capital costs of solar collector, heat exchanger and distillation chamber per unit area, respectively, Rs/m²

$C_T$ — Annual cost of the total system including solar collector and heat exchanger, Rs/m²

$C_w$ — Cost of unit mass of distilled water, Rs/kg

$f_c, f_h, f_S$ — Capital recovery factors for solar collector, heat exchanger and distillation chamber, respectively

$F_c, F_h, F_S$ — Sinking fund factors for solar collector, heat exchanger and distillation chamber, respectively
$M_c, M_h, M_S$ — Annual maintenance costs of solar collector, heat exchanger and distillation chamber as a fraction of their respective capital costs, Rs

$M_d$ — Daily distillate output per unit area, kg/m²

$M_{e,i}$ — Instantaneous distillate output from $i$th stage, kg/m²s

$M_y$ — Annual average distillate output of solar still, kg/m²y

$N$ — Number of stages

$N_{d,m}$ — Number of days in the $m$th month

$R$ — Ratio of solar collector area to the base area of MSST solar still

$S_c, S_h, S_S$ — Salvage values of solar collector, heat exchanger and distillation chamber as a fraction of their respective capital costs, Rs

$t$ — time, h

References


