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Experimental investigation on the effect of basin pressure in a single basin solar still

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ABSTRACT

This paper aims to investigate the effect of initial basin pressure on the productivity of solar still. A single slope single basin solar still of base area 0.49 m^2 was fabricated using galvanized iron sheets and tested in the terrace of Velammal Engineering College, Chennai (13°09′0.08″N, 80°11′31.22″E). The initial basin pressure of the solar still was modified using a reciprocating pump. The freshwater yield of the still was measured at various operating pressures such as 25, 50, 75, and 101.32 kPa (atmospheric pressure). It was observed that the yield of the solar still increased by 67.53%, 34.49%, and 10.72%, respectively, when compared with atmospheric pressure operation. Based on the experimental results, it can be concluded that the reduction in pressure inside the solar still facilitates the process of evaporation and condensation thus leading to higher productivity.

Keywords: Low-pressure solar still; Solar still yield

1. Introduction

For the survival of mankind, freshwater is essential. Although more than two-thirds of the earth has been covered with water, only about 0.014% of global water can be used directly for human and industrial purposes [1]. The ever increasing demand for the limited supply of water due to a blooming human population and industrialization has resulted in a worldwide imbalance and it poses a major threat in developing countries. Recently, various desalination techniques have been employed to convert the vast resource of saline water into potable water such as reverse osmosis, multi-stage flash distillation, multi-effect distillation, and electrodialysis [2]. These techniques utilize depleting fossil energy.

Solar still, a simple, economic device that utilizes solar energy in the process of distillation is a viable solution to resolve the demand of freshwater in arid remote areas where plenty of solar energy is available. Since the solar still operates with renewable solar energy it has zero operational cost [3]. The major drawback of solar still is its low productivity [4].

Various researches are carried out across the globe on improving the productivity of the solar still in recent times [5–9]. Boubekri and Chaker [10] analyzed the effect of external and internal reflectors in a solar still to improve productivity and observed an increase of 72.8% in winter. Prakash and Natarajan [11] conducted an experiment with aluminum, galvanized iron, and glass as the basin material and the results show that the productivity is high when aluminum is used as the basin material. It is observed that the cost of 1 L of water from the aluminum solar still is twice that of galvanized iron solar still. The effect of uniform water flow over the condensing cover resulted in 100%

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increment in productivity due to reduced glass cover temperature [12]. Pandey [13] analyzed the effect of methylene blue dye on the performance of a single basin and double basin solar still and observed an increase in productivity of 16.2% and 57.5%, respectively. The presence of dye increased the temperature of the feed water as a result of increased solar radiation absorption. Rajaseenivasan et al. [14] increased the productivity of the solar still by fabricating and testing double basin solar still and observed an increase of 85% in the proposed model compared to conventional solar still. The addition of highly conductive nano-fluids to the water will improve the solar absorption capacity thus leading to increased water temperature and higher productivity. Aluminum oxide, zinc oxide, copper oxide, and tin oxide are the common nanofluids that improve the thermal characteristics of water [15]. Rufuss et al. [16] compared the productivity of solar still integrated with phase change material and nano impregnated phase change material. Copper oxide nanoparticles were impregnated in paraffin to form nanophase change material. An increase of 35% on productivity was observed in solar still using nanophase change material as against solar still with phase change material without nano impregnation. Kabeel et al. [17] investigated the effect of adding cuprous oxide nanoparticles in the black paint of the solar still walls. It was observed the distillate output of the solar still increased by 16% and 25% with the presence of copper oxide nanoparticles at a weight concentration of 10% and 40%, respectively, due to enhanced heat transfer rate. Vigneswaran et al. [18] analyzed the effect of PCM on the nocturnal productivity of solar still. The daily yield of solar still without PCM, solar still with single PCM, and solar still with two PCM were tested under identical weather conditions. The prolonged discharge of heat energy stored in multiple PCM resulted in the yield of 4.40 $L/m^2/d$, which was 19.6% and 9.5% higher than the yield of solar still without PCM and with single PCM, respectively. Zanganeh et al. [19] compared the effect of drop-wise and film-wise condensation on the condensate yield of a single basin single slope solar still. Nano silicon solution was applied at the condensing surface to alter its wettability. It was observed that, at higher surface inclination angles, drop-wise condensation produced more distillate.

Providing vacuum inside the solar still results in a significant increase in its productivity by increasing its evaporation and condensation rate [20]. The evaporation rate is improved an innovative water desalination system utilizing gravity and atmospheric pressure to create a vacuum inside the solar still was designed and analyzed [21,22]. The creation of a vacuum inside the desalination system resulted in a two-fold increase in productivity. The system was required to be placed at an elevation of 10 m above mean sea level in order to create a vacuum which stepped up the maintenance and cost of the system. Sriram et al. [23] fabricated and tested a single basin double slope low-pressure solar still. Maintaining a pressure of 50 mm of Hg inside the still increased the productivity by 50.75% but employing an external condenser for condensation increases the vapor loss and also the cost of the system. Kabeel et al. [24] enhanced the performance of a solar still by using nanoparticles and vacuum. Additional of cuprous oxide nanoparticles resulted in a productivity increase of 133.64% and 93.87% with and without vacuum. Omara et al. [25] compared the productivity of corrugated wick solar still with conventional solar still. The corrugated wick solar still increased the productivity of solar still by 180% when operated under vacuum conditions and with reflectors. The modified still with reflectors had an increase in productivity by 285% and 254% when operated under vacuum condition with cuprous oxide and aluminum oxide nanoparticles respectively. Xie et al. [26] conducted an investigation on the performance of tubular solar still under vacuum conditions. With the reduction in operating pressure, the energy utilization efficiency of the system increased by 80% when compared with normal operating conditions. Yan et al. [27] investigated the effect of vacuum operating pressure on the productivity of two-effect solar still. It was observed that the freshwater yield rate at 20 kPa was more than twice at atmospheric pressure. It was also predicted that the vacuum operation has higher economic feasibility for a multi-effect solar still.

After reviewing the previous works, it is concluded that the productivity of solar still is enhanced when operated under vacuum condition, but the conventional solar still needs to be modified with the provision of an external condenser and a photovoltaic cell to provide electrical input for the continuous operation of vacuum fan which adds up to the cost of the still. In this research work, a new design of low-pressure solar still which does not require an external condenser and continuous operation of vacuum pump is presented. A single slope single basin solar still was fabricated and tested for various initial vacuum pressures inside the basin such as 25, 50, and 75 kPa. The results are compared with the productivity of the solar still at atmospheric pressure inside the basin.

2. Materials and methods

2.1. System description and operating principle

A schematic representation of the experimental solar still is shown in Fig. 1. A single slope single basin solar still was fabricated using a 0.004 m thick galvanized iron sheet as the base material and is covered at the top using a glass of 0.004 m thickness. The usage of galvanized iron is to avoid the formation of rust on the inner side of the basin and also for its high thermal conductivity. Glass is the preferred material for the cover since it has high solar transmittance for various angles of incidence [28]. The glass cover is positioned facing south and inclined at an angle of 13° in accordance with the latitude of Chennai, India for maximum solar incidence [29]. The whole basin surface is coated with black paint to increase the solar absorptivity. The base area of the solar still is 0.7 m × 0.7 m. The height of the solar still was 0.2 m from the lower end of the glass and 0.362 m from the upper end of the glass cover. A gap of 0.15 m is provided between the ground and the solar still to avoid the conductive heat loss through the bottom surface of the still. A reciprocating piston-type vacuum pump was used to achieve the required pressure inside the solar still. A separate water supply tank made of GI sheet is provided adjacent to the solar still. The solar still is connected with the water supply tank and the water storage tank through pipes with a one-way valve.

This arrangement is to prevent air leakage into the solar still during the supply of brackish water and collection of condensed water. Sealants are used to fill the gap between the glass cover and the still basin to prevent any leakage. K-type thermocouples with a multichannel digital display system were used to measure the temperature of basin water, feedwater, the inner side of the glass cover, and the atmospheric air. Global solar radiation was recorded by a thermoelectric pyranometer. Vane type anemometer was used to measure the wind velocity. A small vacuum port is provided in the basin to measure the pressure inside the solar still using a vacuum gauge. The productivity of solar still mainly depends upon the evaporation rate and condensation rate. The effect of vacuum inside the solar still reduces the convective thermal loss from the water which accounts for the reduction in the basin water temperature and also an increase in the condensing cover temperature. It also eliminates the non-condensable gases present in the air which rises up and forms a thermal barrier near the condensing cover, thus increasing the condensation rate. The pressure above the water surface has a dominant effect on the evaporation rate of water. As the pressure reduces, the evaporation rate increases significantly and when the vapor pressure of the water equals the surrounding air pressure, boiling begins. The main objective of this experiment is to investigate the effect of negative atmospheric pressure inside the solar still. The reduction in pressure inside the solar still will enhance the evaporation and condensation rate thus increasing productivity.

2.2. Experimental procedure

The fabricated solar still as shown in Fig. 2 was tested on the terrace of TVS Block, Velammal Engineering College, Chennai, India (13°09′0.08″N, 80°11′31.22″E). Initially, the solar still was tested for its productivity without any pressure reduction inside it. The experiments were commenced around 9 a.m. and continued up to 6 p.m. The feed water was supplied up to a depth of 2 cm in the still. The hourly experimental data such as solar radiation flux density, the temperature of the basin water, the temperature of the inner glass cover, wind speed, and potable water output were recorded. The experiment was repeated with an initial basin pressure of 25, 50, and 75 kPa obtained using a vacuum pump. The comparison of distilled water output at each pressure was analyzed. The cumulative yield per day at each pressure condition has also been recorded.

2.3. Theoretical analysis

The distillate output from the single basin solar still can be obtained using Eqs. (1)–(4) [30].

The hourly productivity of solar still per m^2 (m_w) can be calculated using Eq. (1):

$$m_w = \frac{q_{\text{ew}}}{L} \times 3,600 \quad (1)$$

where q_{ew} is the evaporative heat transfer rate per unit area between basin water and the inner surface of the glass cover. q_{ew} can be found using the relation in Eq. (2):

$$q_{\text{ew}} = h_{\text{ew}} \times \left(T_w - T_g\right) \quad (2)$$

where h_{ew} is the evaporative heat transfer coefficient and can be determined using Dunkle's relation in Eq. (3):

Fig. 2. Photograph of the experimental setup.

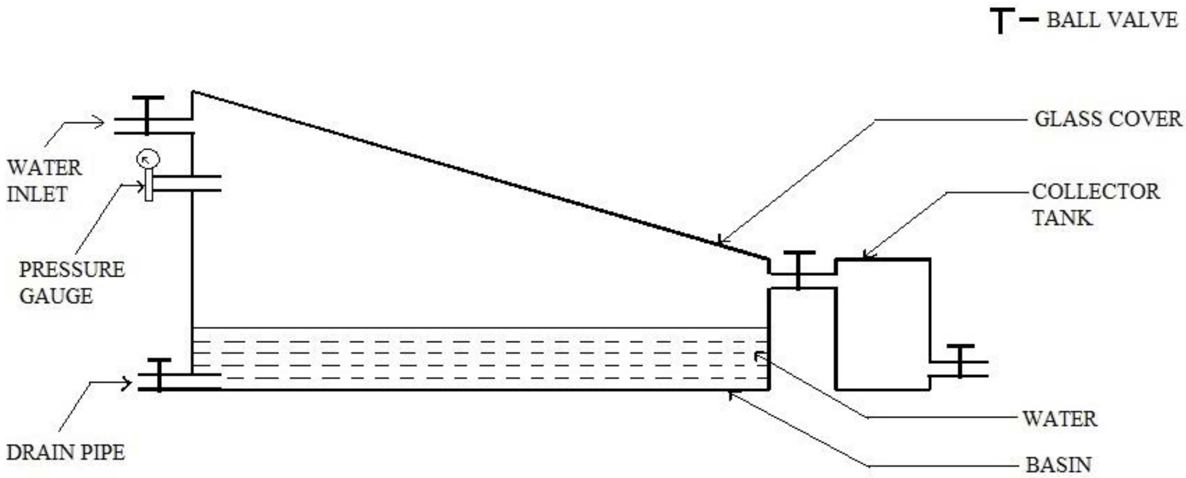

Fig. 1. Schematic diagram of the proposed solar still.

$$h_{ew} = 0.0163 \times h_{cw} \times \frac{P_w - P_{ci}}{T_w - T_{ci}} \quad (3)$$

where h_{cw} is the convective heat transfer coefficient, P_w and P_{ci} are the saturation vapor pressure at basin water temperature T_w, and inner glass cover temperature T_{ci}, respectively.

The convective heat transfer coefficient h_{cw} can be determined using the dimensionless Nusselt number, which is given in Eq. (4):

$$\text{Nu} = \frac{h_{cw}}{k/d} = C\left(\text{Gr} \cdot \text{Pr}\right)^n \quad (4)$$

where k is the conductivity of the vapor, Gr is the Grashoff number, Pr is the Prandtl number, C and n are constants that depend on the geometry of the surface and the flow regime, which is characterized by the range of Rayleigh number.

2.4. Experimental uncertainty analysis

The uncertainty limits of various measuring instruments used in this experiment are given in Table 1. The percentage of uncertainty is calculated for thermocouples, pyranometer, anemometer, vacuum gauge, and measuring jar. The minimum uncertainty in an instrument is equal to the ratio between its least count and least value measured during experimentation [1].

3. Results and discussion

Fig. 3. depicts the variation of solar flux density measured by the pyranometer during the experimental period. The solar radiation is consistent on all the experimenting days. The incident radiation increases in the daytime and reaches the peak value around 01.00 p.m. and then decreases gradually forming a parabolic curve with time. The variation of wind velocity is shown in Fig. 4. Wind velocity affects the productivity of the solar still through variation of the condensing cover temperature. Since the experiment was conducted at a height of 18 m above the ground, the wind velocity was higher. Higher wind velocity aids in removing the heat from the glass cover through convection thus reducing its temperature and increase the condensation rate and productivity.

Temperature measurements were taken at three significant points in the solar still. The temperature of basin water, inner glass cover, and the surrounding environment have a significant effect on the yield of the solar still. Figs. 5–7 show the variation of ambient temperature, basin water temperature, and inner glass cover temperature, respectively. The average ambient temperature is uniform on all days. The basin water temperature increases with an increase in solar radiation and reaches its maximum value around 02.00 p.m. The inner glass cover temperature also follows the same parabolic path since it depends on the basin water temperature

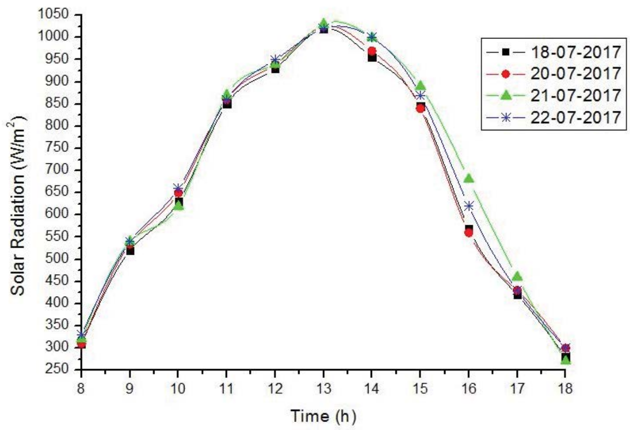

Fig. 3. Hourly variation of solar flux density on various experimentation days.

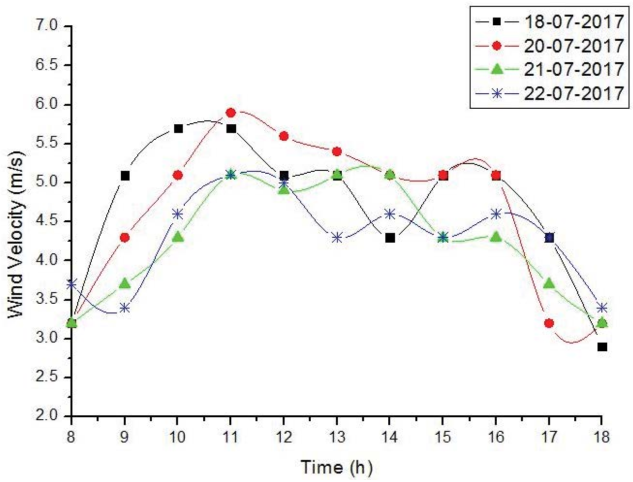

Fig. 4. Hourly variation of wind velocity on various experimentation days.

Table 1
Uncertainty analysis of measuring instruments

S. No	Measuring instrument	Symbol	Range	Accuracy	Uncertainty (%)
1	K type thermocouple	T	0°C–100°C	±0.1°C	0.3
2	Pyranometer	I	0–2,500 W/m^2	±1 W/m^2	0.4
3	Anemometer	WV	0–32.4 m/s	±0.1 m/s	3.6
4	Vacuum gauge	P	0.01–200 kPa	±0.01 kPa	0.04
5	Measuring jar	V	0–1,000 mL	±1,840 mL	10

and solar radiation. The variation of absolute pressure inside the solar still during the operating time is depicted in Fig. 8.

The effect of vacuum pressure inside the solar still on productivity is shown in Fig. 9. The still was tested under standard atmospheric conditions and the experiment was repeated with various vacuum pressures such as 75, 50, and 25 kPa. The pump was operated before the start of the experiment and the required pressure was maintained. The modified design ensures the supply and collection of water are carried out without any leakage. The experiment was started at 09.00 a.m. and hourly distillation output was measured. It is observed that the reduction in pressure inside the solar still enhances productivity due to an increase in evaporation rate and condensation rate as discussed above. The productivity of the vacuum pressure was compared with the productivity at atmospheric pressure conditions. The variation in productivity is lower for 75 kPa pressure since the pressure rise inside the solar still reaches the atmospheric pressure during operation. Pressure rise inside the solar still was due to the evaporation of dissolved gases in water and expansion of air and vapor during daytime. The productivity enhancement for 50 and 25 kPa is significantly higher.

The cumulative still productivity per day for various initial basin pressures is as shown in Fig. 10. It is observed that the cumulative productivity increases significantly for basin pressure below 50 kPa. It is observed that the total productivity of the solar still is higher for lower basin pressure due to high nocturnal productivity.

3.1. Comparison with previous works

The comparison of the present work with previous studies of low-pressure solar still is shown in Table 2.

3.2. Economic analysis

The estimation of potable water cost and payback period (PBP) of low-pressure solar still is presented in Table 3. The cost of potable water and PBP depends on the fabrication cost, operating cost, and maintenance cost. The cost of feed water may be neglected [32]. The unit cost of potable water (C_w) is the ratio of the total cost of the solar still

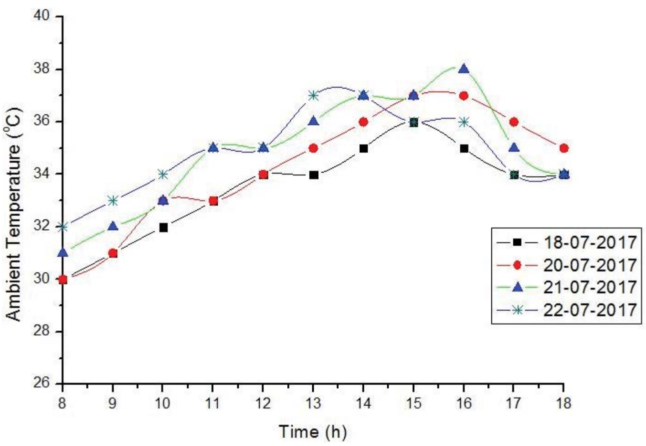

Fig. 5. Hourly variation of ambient temperature on various experimentation days.

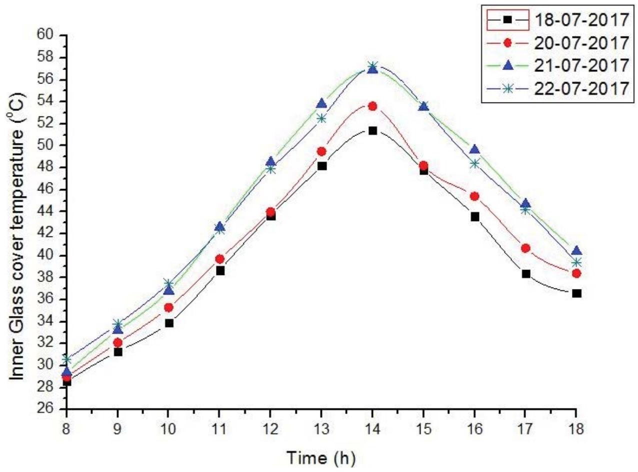

Fig. 7. Hourly variations of inner glass cover temperature on various experimentation days.

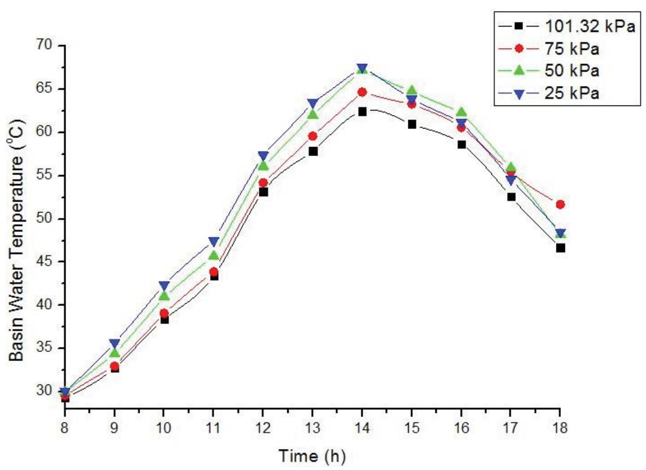

Fig. 6. Hourly variation of basin water temperature at various operating pressure.

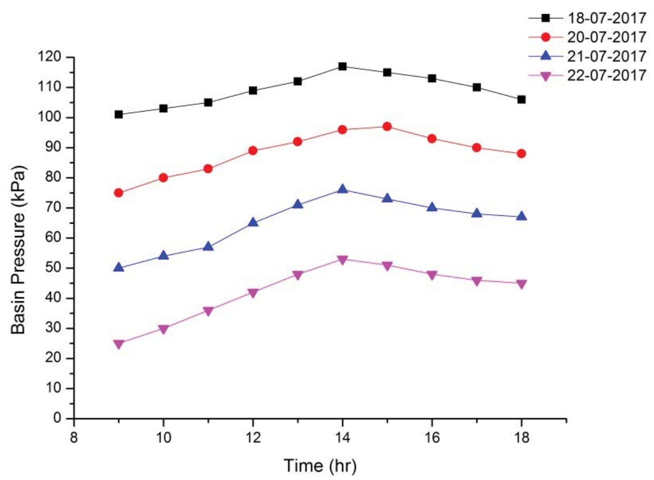

Fig. 8. Hourly variations of basin pressure on various experimentation days.

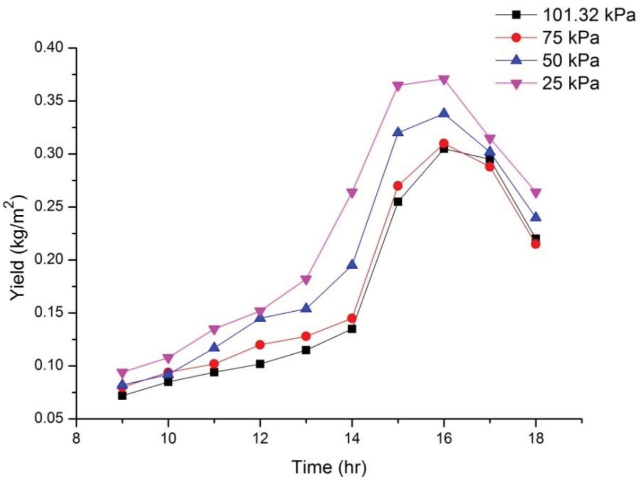

Fig. 9. Solar still productivity at various initial basin pressures.

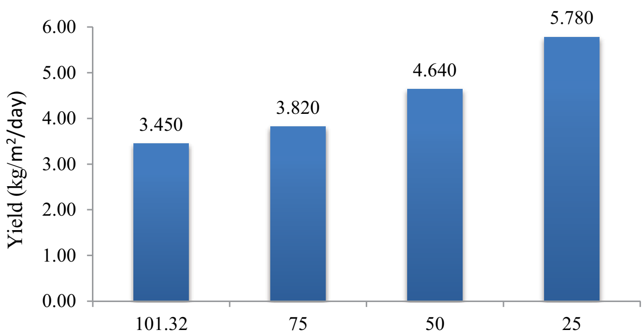

Fig. 10. Total solar still productivity per day at various initial basin pressures.

per annum (TC_s) and the average yield of the solar still per annum (m_y). PBP is the ratio of the investment cost of the still (IC_s) and the net profit generated per annum (P_y). Table 3 shows the detailed economic analysis of the proposed solar still. The average service life of 10 y is assumed for the solar still. The average cost of potable water in India is Rs. 20/L. The operating and maintenance cost of the solar still includes the cost involved in operating the vacuum pump, regular cleaning of the glass cover, removal of scaling inside the basin, and collection of potable water regularly.

Hence,

$$C_w = \frac{TC_s}{m_y} \tag{5}$$

$$PBP = \frac{IC_s}{P_y} \tag{6}$$

where

Total cost of the still (TC_s) = Fabrication cost + Maintenance cost + Operating cost

Table 3
Economic analysis

S. No	Particulars	Cost in INR
1	Fabrication cost	9,000
2	Operating cost	3,600/y
3	Maintenance cost	1,800/y
4	Cost of potable water produced	4.8/L
5	Net profit earned	19,760/y
6	Payback period	265 d

Table 2
Comparison with similar works

Reference	Type of still	Base area (m^2)	Operating pressure (kPa)	Yield (kg/m^2 d)
Sriram et al. [23]	Single slope single basin	1.3	6.6	3.475
Al-Kharabsheh and Goswami [22]	Single slope single basin with cuprous oxide nanoparticles	0.5	Vacuum	2.240
	Single slope single basin with aluminum oxide nanoparticles	0.5	Vacuum	2.095
Omara et al. [25]	Corrugated wick still with reflectors	0.5	Vacuum	5.750
	Corrugated wick sill with reflectors and cuprous oxide nanoparticles	0.5	Vacuum	7.525
	Corrugated wick sill with reflectors and cuprous oxide nanoparticles	0.5	Vacuum	7.800
Xie et al. [31]	Three effect tubular still	0.13, 0.17, and 0.18	1 atm	3.27
			60	6.32
			40	7.05
			20	4.28
Present work	Single basin single slope solar still	0.49	1 atm	3.45
			75	3.82
			50	4.64
			25	5.78

Net profit earned (P_y) = (Cost of potable water – Cost of potable water produced) × Average yield

Cost of potable water produced = Total cost of the still/Average yield

4. Conclusions

A single basin single slope solar still operating under various initial basin pressures were investigated experimentally. Based on the experimental work, the effect of initial basin pressure on productivity was studied and the following conclusions were drawn:

- Vacuum pressure operation inside the solar still increases the distillate output of the still due to enhanced evaporation and condensation rate.
- The temperature of the basin water increased with a reduction in operating pressure due to lower convection heat loss. A peak temperature of 67°C was obtained when the still was operated at 25 kPa.
- The distillate yield increased by 67.53%, 34.49%, and 10.72% when the solar still was operated with an initial basin pressure of 25, 50, and 75 kPa, respectively.
- Vacuum operation increases the operating and maintenance cost of the still. The unit cost of potable water produced was Rs. 4.8/L. A multi-effect solar still with vacuum operation may further enhance the economic feasibility.

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