

# Experimental study on conventional and stepped solar stills coupled with evacuated tube collector solar water heater

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## ABSTRACT

Experimentation on conventional and stepped type solar still coupled with evacuated tube collector (ETC) solar water heater was performed in the climatic condition of Hisar. The conventional solar still was tested at a water depth of 6 cm and the stepped solar still at 50, 75 and 100 ml/min flow rate respectively. The temperature of water and inner glass cover in stepped solar still was observed higher in comparison to conventional solar still. Dunkle's model was used to predict various heat transfer coefficients for both conventional and stepped solar still. In stepped solar still the values of internal convective heat transfer coefficients were observed higher at lower water flow rate. The maximum value of internal convective heat transfer coefficient for stepped solar still was evaluated to be  $3.45 \text{ W/m}^2\text{ }^\circ\text{C}$  and the maximum evaporative heat transfer coefficient was obtained as  $30.74 \text{ W/m}^2\text{ }^\circ\text{C}$ . The values of internal convective, evaporative and radiative heat transfer coefficients for conventional solar still were observed to vary from  $1.02\text{-}2.53 \text{ W/m}^2\text{ }^\circ\text{C}$ ,  $3.91\text{-}15.3 \text{ W/m}^2\text{ }^\circ\text{C}$  and  $5.67\text{-}7.57 \text{ W/m}^2\text{ }^\circ\text{C}$  respectively. The maximum value of external convective heat transfer coefficients ( $h_{cg}$ ) for both solar stills were same and found to be  $4.9 \text{ W/m}^2\text{ }^\circ\text{C}$ .

**Keywords:** Stepped solar still; Evacuated tube collector; water flow rate; Dunkle's model

## 1. INTRODUCTION

About two third of earth surface is covered with water. Approximately 97% of the earth water is salty, and around 2.5% is available as fresh water. Less than 1% fresh water is within reach of human being. Due to increasing population and rapidly developing industrialization, the demand of fresh water is also increased. Human that living on earth requires nearly 30-50 l/day of potable water for drinking, cooking and other purposes. But the availability of fresh water is shrinking day by day due to poor water management. Contaminated water always contains some harmful bacteria, viruses, and dissolved materials, chemical and physical contaminants which cause serious damage of health on consumption [1]. Distillation of brackish water is a good option for water purification. Solar distillation process is a renewable energy based process and it has main advantage of being eco-friendly, easy to operate, zero fuel cost and low maintenance cost. But this technology has some disadvantage being a slow process and occupies large space. Some continuously efforts are

being made to make this technology more efficient since last decades [2]. Delyannis (1872) gives the first background report on solar distillation work, and this work done by Carlos Wilson in Las Salinas[3]. Manchanda and Kumar [4] also reviewed various water desalination techniques on active solar distillation method. Tiwari and Nath [5] studied different solar distillation design, modeling and their fundamentals. Many researcher worked on different type of parameters for improving water distillation including design parameters like (tilt angle of condensation, shape of still, size of still), climatic parameter like (sun radiation, wind velocity, ambient temperature) and some operational parameters like (external heat sources, insulation thickness, water depth, phase change material). Velmurugana and Srithar [6] reviewed different type of researches for improvement in the productivity of solar still. Kabeel and Omara [7] experimental studied techniques to improve the performance of the stepped solar still. Ziabari et al. [8] investigated problems causing cease of productivity of solar still site in arid region of Iran. They proposed different modified designs of cascade solar still to improve its performance. They theoretically analyzed the performance and found a modified improved design. The average fresh water production for the modified cascade solar still was around 6.7 l/day m<sup>2</sup>, which shows 26% increase in comparison with the initial site's units. Pillai [9] studied and reviewed performance of solar still under sealed and unsealed condition. They also experimentally investigate weir solar still with latent heat thermal energy storage system (LHTESS). Asadi et al. [10] studied different type of applications of solar still in domestic and waste water treatment. Gawande et al. [11] studied effect of shape of absorber surface on the performance of stepped type solar still. Three types of absorber surfaces flat, convex and concave inside solar still were investigated. Convex and concave type absorber surfaces provided 56.6% and 29.4% more productivity than flat shape surface for the stepped solar still respectively. Abdullah et al. [12] designed a new stepped solar still coupled with a solar air heater, storage material and glass cover cooling for improving the performance of solar still. Abdallah and Badran [13] experimentally investigated the effect of sun tracking on solar still. Omara et al. [14] showed the effect of condenser and reflector on stepped solar still. The output of designed stepped solar still with reflectors was observed 75% higher than that of ordinary stepped solar still. El-Samadony et al. [15] used internal and external mirror with exterior condenser on stepped solar still. Sivakumar et al. [16] studied different parameter and various techniques that can improve the performance of solar still. Abad et al. [17] carried out experimentation on pulsating heat pipe integrated solar still. Pulsating heat pipe had benefit like fast responsive, flexible and higher performance thermal conducting device, etc. They concluded that distillate output of the present still increased by 40% by use of pulsating heat pipe compared with conventional solar still. El-Samadony and Kabeel [18] showed the effect of film cooling depth, flow rate, inlet temperature, and air wind speed on the stepped solar still to improve the output performance. Velmurugan et al. [19] tested a stepped solar still with an effluent settling tank. Muftah et al. [20] studied and showed the effect of different kind of parameters on the productivity of solar still.

In this paper, experimentation on conventional and stepped solar still has been performed and their thermal performance has been compared in the climatic condition of Hisar.

## II.EXPERIMENTAL SET-UP

Photographic view of the experimental set-up and the specifications of different components are shown in figure1 and table 1-2. The setup mainly comprises of same size of stepped and conventional solar still, storage tank, and evacuated tube solar water heater. Evacuated tube solar water heater was used to provide preheated water in the solar stills. Thermocouples connected with digital temperature indicator were used to measure temperatures at different locations in the solar still. A vane type digital anemometer was used to measure wind velocity. Solar power meter was used to measure the solar intensity of solar still. The experiments have been run during day time from 8:00 a.m. to 17:00 p.m. The hot water from solar water heater is supplied to conventional solar still to maintain a water depth of 6 cm. But in the stepped solar still, the hot water was supplied at different flow rates of 50, 75, and 100 ml/min on different days respectively. Solar radiation intensity, temperatures at different locations, wind velocity measurements were done on hourly basis. All these measurements were used to determine various heat transfer coefficients using Dunkel's model.



**Fig.1 Experimental Set-up**

**Table:1 Specifications of conventional and stepped solar stills**

| Item                              | Conventional solar still | Stepped solar still |
|-----------------------------------|--------------------------|---------------------|
| Area of basin                     | 0.56 m <sup>2</sup>      | 0.56 m <sup>2</sup> |
| Material of basin                 | Aluminium                | Aluminium           |
| Thickness                         | 0.005 m                  | 0.005m              |
| Larger side length                | 0.53 m                   | 0.53 m              |
| Smaller side length               | 0.23 m                   | 0.23 m              |
| Length of vertical side of step   | -                        | 0.06 m              |
| Length of horizontal side of step | -                        | 0.12 m              |
| Glass cover thickness             | 0.003 m                  | 0.003 m             |
| Insulation thickness              | 0.02 m                   | 0.02 m              |

Table:2 Specifications of evacuated tube solar water heater

| Item                      | Specifications     |
|---------------------------|--------------------|
| Outer diameter of tube    | 5.8 cm             |
| Inner diameter of tube    | 4.7 cm             |
| Length of tube            | 90 cm              |
| Number of tubes           | 5                  |
| Material of tube          | Borosilicate glass |
| Inclination angle of tube | 30°                |

### III.THERMAL ANALYSIS

The heat transfer process in solar still mainly takes place inside the solar still and through outside the glass cover. It can be termed as internal and external heat transfer respectively. Various internal and external heat transfer coefficients are evaluated using the Dunkle's relations which are given in equations 1-5.

#### 3.1 Internal heat transfer coefficients

The internal heat transfer involves three processes-evaporation, convection and radiation. The internal heat transfer coefficients are determined using equations 1-3.

##### 3.1.1 Convective heat transfer coefficient ( $h_{cw}$ )

$$h_{cw} = 0.884 \left[ T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{1/3} \quad (1)$$

The value of partial vapor pressures  $P_w$  and  $P_g$  are determined by

$$P_w = e^{\left[ \frac{25.317 - \frac{5144}{273 + T_w}}{1} \right]}$$

$$P_g = e^{\left[ \frac{25.317 - \frac{5144}{273 + T_g}}{1} \right]}$$

##### 3.1.2 Evaporative heat transfer coefficient ( $h_{ew}$ )

Evaporative heat transfer coefficient is determined by equation (2),

$$h_{ew} = 0.01623 \times h_{cw} \left[ \frac{P_w - P_g}{T_w - T_g} \right] \quad (2)$$

##### 3.1.3 Radiative heat transfer coefficient ( $h_{rw}$ )

Radiation heat transfer coefficient is determined by equation (3),

$$h_{rw} = \varepsilon_{eff} \times \sigma \left[ (T_w + 273)^2 + (T_g + 273)^2 \right] (T_w + T_g + 546) \quad (3)$$

Where,

$$\varepsilon_{eff} = \frac{1}{\left( \frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1 \right)}$$

### 3.2 External heat transfer coefficients

External heat transfer coefficients are determined by equations (4) and (5)[5, 21].

#### 3.2.1 External convective heat transfer coefficient

The external convective heat transfer occurs from outer glass cover to outside atmosphere and determined by equation (4).

$$h_{cg} = 5.7 + 3V \quad (4)$$

#### 3.2.2 Radiative heat transfer coefficient

The radiative heat transfer coefficient is determined by considering outer glass cover and sky temperatures in equation (5),

$$h_{rg} = \left[ \frac{(T_g + 273)^4 - (T_s + 273)^4}{(T_g - T_s)} \right] \quad (5)$$

Where

$$T_s = T_a - 6$$

## IV.RESULTS AND DISCUSSION

The experiments were performed on evacuated tube collector (ETC) solar water heater coupled conventional and stepped solar stills. The effect of preheated water through ETC on the performance of conventional and stepped solar stills have been analyzed and compared. The effect of water flow rate on the performance of stepped solar still has also been examined. The stepped solar still is tested at a water flow rates of 50, 75 and 100 ml/min while conventional solar still is maintained at a constant water depth of 6 cm. All the experiments were performed on the roof of Mechanical Engineering Department, Guru Jambheshwar University of Science and Technology, Hisar in the month of August 2017 at 8:00 a.m. to 17:00 p.m. The experimental data obtained during the experimentation is shown in the tables 1-3.

**Table 1** Experimental data for conventional solar still (water depth = 6 cm) and stepped solar still (water flow rate = 50 ml/min).

| Conventional solar still |                              |            |               |               |                  |                  |               | Stepped solar still |                  |                  |               |
|--------------------------|------------------------------|------------|---------------|---------------|------------------|------------------|---------------|---------------------|------------------|------------------|---------------|
| TIME                     | $I_t$<br>(W/m <sup>2</sup> ) | V<br>(m/s) | $T_a$<br>(°C) | $T_w$<br>(°C) | $T_{gi}$<br>(°C) | $T_{go}$<br>(°C) | $T_v$<br>(°C) | $T_w$<br>(°C)       | $T_{gi}$<br>(°C) | $T_{go}$<br>(°C) | $T_v$<br>(°C) |
| 8:00                     | 520                          | 1.8        | 31            | 33.4          | 27.6             | 31.4             | 28.4          | 41                  | 28.2             | 32.4             | 39            |
| 9:00                     | 740                          | 2.2        | 34            | 39.3          | 35.4             | 36.8             | 38.2          | 49.2                | 37.4             | 38.2             | 48.1          |
| 10:00                    | 910                          | 1.6        | 35.4          | 46.5          | 40.8             | 41.9             | 43.4          | 56.7                | 40.8             | 41.7             | 55.4          |
| 11:00                    | 1170                         | 1.8        | 37.3          | 52.2          | 42.7             | 42.3             | 49.4          | 66.7                | 48.4             | 44.8             | 65.2          |
| 12:00                    | 1320                         | 2.2        | 43.8          | 58.1          | 51.3             | 48.2             | 54.1          | 73.2                | 59.6             | 50.2             | 70.8          |

|       |      |     |      |      |      |      |      |      |      |      |      |
|-------|------|-----|------|------|------|------|------|------|------|------|------|
| 13:00 | 1460 | 0.2 | 44.1 | 66.2 | 56.0 | 54.8 | 62.5 | 85   | 74.2 | 59.2 | 81   |
| 14:00 | 1330 | 1.2 | 43.6 | 63.2 | 54.2 | 52.6 | 61.2 | 82.7 | 70.5 | 54.5 | 79.3 |
| 15:00 | 1210 | 0.3 | 42.5 | 62   | 53.1 | 51.7 | 58.4 | 74.5 | 61.8 | 53.8 | 73.7 |
| 16:00 | 970  | 0.3 | 40.2 | 59.3 | 45.4 | 46.3 | 56.5 | 65.7 | 47.4 | 49.6 | 64.1 |

**Table 2** Experimental data for conventional solar still (water depth = 6 cm) and stepped solar still (water flow rate = 75 ml/min).

| Conventional solar still |                              |            |               |               |                  |                  |               | Stepped solar still |                  |                  |               |
|--------------------------|------------------------------|------------|---------------|---------------|------------------|------------------|---------------|---------------------|------------------|------------------|---------------|
| TIME                     | $I_t$<br>(W/m <sup>2</sup> ) | V<br>(m/s) | $T_a$<br>(°C) | $T_w$<br>(°C) | $T_{gi}$<br>(°C) | $T_{go}$<br>(°C) | $T_v$<br>(°C) | $T_w$<br>(°C)       | $T_{gi}$<br>(°C) | $T_{go}$<br>(°C) | $T_v$<br>(°C) |
| 8:00                     | 620                          | 0.3        | 31.1          | 36.2          | 32.1             | 33.1             | 34            | 40.1                | 37.4             | 38.1             | 38.3          |
| 9:00                     | 800                          | 0.6        | 32.2          | 40.3          | 36.5             | 37.3             | 38.7          | 45.3                | 41.2             | 43.3             | 42.4          |
| 10:00                    | 1020                         | 1.2        | 34.3          | 44.7          | 41.2             | 43.2             | 42.8          | 51                  | 46.7             | 47.2             | 48.5          |
| 11:00                    | 1190                         | 0.8        | 38.3          | 56.8          | 47.5             | 47.5             | 49.4          | 68.7                | 52.3             | 48.1             | 58.2          |
| 12:00                    | 1280                         | 0.6        | 39.5          | 57.4          | 48.7             | 48.3             | 53.8          | 74.1                | 54.1             | 49.3             | 61.5          |
| 13:00                    | 1423                         | 1.0        | 41.6          | 61.4          | 56.2             | 49.8             | 58.4          | 77.1                | 56.1             | 52.2             | 63.3          |
| 14:00                    | 1330                         | 0.5        | 41.1          | 60.1          | 54.3             | 54.3             | 57.4          | 71.2                | 53.2             | 49.1             | 59.3          |
| 15:00                    | 920                          | 1.0        | 39.3          | 55.3          | 51.1             | 51.1             | 53            | 63.3                | 51.4             | 47.4             | 57.1          |
| 16:00                    | 610                          | 0.4        | 38.4          | 54.1          | 48.2             | 49.8             | 51.2          | 50.4                | 45.3             | 46.6             | 47.2          |
| 17:00                    | 510                          | 0.6        | 35.2          | 50.3          | 44.5             | 46.2             | 47.6          | 46.2                | 41.7             | 44.3             | 44.1          |

**Table 3** Experimental data for conventional solar still (water depth = 6 cm) and stepped solar still (water flow rate = 100 ml/min).

| Conventional solar still |                              |            |               |               |                  |                  |               | Stepped solar still |                  |                  |               |
|--------------------------|------------------------------|------------|---------------|---------------|------------------|------------------|---------------|---------------------|------------------|------------------|---------------|
| TIME                     | $I_t$<br>(W/m <sup>2</sup> ) | V<br>(m/s) | $T_a$<br>(°C) | $T_w$<br>(°C) | $T_{gi}$<br>(°C) | $T_{go}$<br>(°C) | $T_v$<br>(°C) | $T_w$<br>(°C)       | $T_{gi}$<br>(°C) | $T_{go}$<br>(°C) | $T_v$<br>(°C) |
| 8:00                     | 640                          | 0.5        | 31.2          | 39.2          | 38.1             | 39.3             | 39            | 39.8                | 38.2             | 40.4             | 39.1          |
| 9:00                     | 883                          | 0.8        | 36.7          | 42.2          | 39.7             | 41.2             | 41.5          | 45.4                | 40.3             | 42.2             | 42.9          |
| 10:00                    | 940                          | 1.4        | 39.5          | 47.3          | 42.4             | 43.6             | 46.7          | 51.6                | 45.7             | 47.2             | 48.3          |
| 11:00                    | 1200                         | 2.1        | 41.6          | 52.4          | 46.3             | 45.4             | 50.1          | 59.8                | 56.2             | 48.3             | 57.2          |
| 12:00                    | 1350                         | 2.1        | 42.1          | 59.7          | 49.5             | 46.2             | 57.2          | 68.7                | 61.3             | 53.5             | 65.4          |
| 13:00                    | 1545                         | 0.8        | 43.2          | 63.7          | 54.1             | 52.0             | 61.5          | 76.3                | 62.2             | 59.1             | 68.1          |
| 14:00                    | 1430                         | 0.5        | 42.7          | 60.3          | 53.1             | 51.1             | 58.2          | 72.4                | 61.8             | 57.2             | 70.5          |
| 15:00                    | 1200                         | 0.7        | 41.5          | 57.3          | 51.2             | 48.5             | 55.4          | 68.1                | 60.2             | 56.1             | 62.4          |
| 16:00                    | 1050                         | 1.0        | 40.2          | 54.5          | 48.3             | 49.4             | 52.3          | 63.5                | 54.4             | 55.3             | 58.3          |
| 17:00                    | 850                          | 1.2        | 38.3          | 48.1          | 43.5             | 45.2             | 46.4          | 59.4                | 50.2             | 52.3             | 56.2          |

Higher temperature difference between internal glass cover and water was observed for stepped solar still than conventional solar still. The maximum water temperature of 85°C at 13:00 p.m. in stepped solar still was observed at a flow rate of 50 ml/min while in conventional solar still the maximum water temperature of 66.2°C was observed. The water vapor temperature was observed considerable higher in stepped solar still than conventional still. The outer glass cover temperature was observed to increase with increase of solar intensity. Various heat transfer coefficient for conventional and stepped solar still are evaluated using Dunkle's model which are shown in table 4-6.

**Table 4** Heat transfer coefficients for conventional solar still (water depth = 6 cm) and stepped solar still (water flow rate = 75 ml/min)

| Conventional solar still |                                   |                                   |                                   | Stepped solar still               |                                   |                                   |
|--------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| TIME                     | $h_{cw}$<br>(W/m <sup>2</sup> °C) | $h_{ew}$<br>(W/m <sup>2</sup> °C) | $h_{rw}$<br>(W/m <sup>2</sup> °C) | $h_{cw}$<br>(W/m <sup>2</sup> °C) | $h_{ew}$<br>(W/m <sup>2</sup> °C) | $h_{rw}$<br>(W/m <sup>2</sup> °C) |
| 8:00                     | 1.72                              | 3.91                              | 5.67                              | 2.28                              | 4.82                              | 5.91                              |
| 9:00                     | 1.55                              | 5.43                              | 6.06                              | 2.33                              | 7.20                              | 6.42                              |
| 10:00                    | 1.82                              | 7.26                              | 6.44                              | 2.67                              | 9.23                              | 6.76                              |
| 11:00                    | 2.22                              | 8.63                              | 6.68                              | 3.01                              | 13.43                             | 7.33                              |
| 12:00                    | 2.09                              | 11.74                             | 7.14                              | 3.15                              | 18.93                             | 7.93                              |
| 13:00                    | 2.53                              | 15.3                              | 7.57                              | 3.40                              | 30.79                             | 8.90                              |
| 14:00                    | 2.37                              | 13.87                             | 7.40                              | 3.07                              | 27.68                             | 8.67                              |
| 15:00                    | 2.34                              | 13.23                             | 7.33                              | 2.92                              | 20.22                             | 8.06                              |
| 16:00                    | 2.06                              | 10.73                             | 6.99                              | 2.70                              | 12.89                             | 7.27                              |
| 17:00                    | 1.90                              | 8.97                              | 6.72                              | 2.59                              | 10.35                             | 6.87                              |

**Table 5** Heat transfer coefficients for conventional solar still (water depth = 6 cm) and stepped solar still (water flow rate = 75 ml/min)

| Conventional solar still |                                   |                                   |                                   | Stepped solar still               |                                   |                                   |
|--------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| TIME                     | $h_{cw}$<br>(W/m <sup>2</sup> °C) | $h_{ew}$<br>(W/m <sup>2</sup> °C) | $h_{rw}$<br>(W/m <sup>2</sup> °C) | $h_{cw}$<br>(W/m <sup>2</sup> °C) | $h_{ew}$<br>(W/m <sup>2</sup> °C) | $h_{rw}$<br>(W/m <sup>2</sup> °C) |
| 8:00                     | 1.55                              | 4.66                              | 5.88                              | 1.38                              | 4.96                              | 6.15                              |
| 9:00                     | 1.55                              | 5.70                              | 6.12                              | 1.63                              | 6.90                              | 6.42                              |
| 10:00                    | 1.54                              | 7.03                              | 6.40                              | 1.71                              | 9.55                              | 6.76                              |
| 11:00                    | 2.28                              | 10.57                             | 6.97                              | 2.69                              | 15.23                             | 7.53                              |
| 12:00                    | 2.41                              | 12.53                             | 7.24                              | 3.30                              | 19.87                             | 7.78                              |

|       |      |       |      |      |       |      |
|-------|------|-------|------|------|-------|------|
| 13:00 | 2.33 | 14.78 | 7.51 | 3.45 | 26.29 | 8.85 |
| 14:00 | 2.02 | 13.01 | 7.30 | 3.12 | 20.62 | 7.65 |
| 15:00 | 1.95 | 11.00 | 7.04 | 2.58 | 16.63 | 7.32 |
| 16:00 | 1.84 | 10.00 | 6.91 | 1.80 | 11.39 | 6.7  |
| 17:00 | 1.79 | 8.78  | 6.70 | 1.69 | 10.08 | 6.46 |

**Table 6** Heat transfer coefficients for conventional solar still (water depth = 6 cm) and stepped solar still (water flow rate = 75 ml/min)

| TIME  | Conventional solar still          |                                   |                                   | Stepped solar still               |                                   |                                   |
|-------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
|       | $h_{cw}$<br>(W/m <sup>2</sup> °C) | $h_{ew}$<br>(W/m <sup>2</sup> °C) | $h_{rw}$<br>(W/m <sup>2</sup> °C) | $h_{cw}$<br>(W/m <sup>2</sup> °C) | $h_{ew}$<br>(W/m <sup>2</sup> °C) | $h_{rw}$<br>(W/m <sup>2</sup> °C) |
| 8:00  | 1.02                              | 4.44                              | 6.14                              | 1.16                              | 4.86                              | 6.16                              |
| 9:00  | 1.36                              | 5.68                              | 6.28                              | 1.75                              | 6.80                              | 6.39                              |
| 10:00 | 1.86                              | 7.19                              | 6.54                              | 1.90                              | 9.15                              | 6.75                              |
| 11:00 | 2.15                              | 9.25                              | 6.86                              | 1.73                              | 15.03                             | 7.36                              |
| 12:00 | 2.40                              | 10.97                             | 7.13                              | 2.35                              | 19.57                             | 7.83                              |
| 13:00 | 2.4                               | 13.88                             | 7.42                              | 3.07                              | 24.29                             | 8.14                              |
| 14:00 | 2.16                              | 12.18                             | 7.27                              | 2.72                              | 19.62                             | 7.98                              |
| 15:00 | 2.01                              | 10.08                             | 7.11                              | 2.39                              | 16.63                             | 7.78                              |
| 16:00 | 1.87                              | 7.55                              | 6.93                              | 2.39                              | 13.39                             | 7.42                              |
| 17:00 | 1.72                              | 7.03                              | 6.57                              | 2.32                              | 11.08                             | 7.15                              |

In the conventional solar still, the internal convective ( $h_{cw}$ ), evaporative ( $h_{ew}$ ) and radiative ( $h_{rw}$ ) heat transfer coefficient was observed vary from 1.02-2.53 W/m<sup>2</sup>°C, 3.91-15.3 W/m<sup>2</sup>°C and 5.67-7.57 W/m<sup>2</sup>°C respectively. In the stepped solar still, higher values of convective heat transfer coefficient were observed at lower flow rate. The maximum and minimum value of convective heat transfer coefficient in stepped solar still was observed 2.53 and 1.02 at 50 ml/min flow. The maximum value of evaporative and radiative heat transfer coefficient was observed 15.3 and 7.57 W/m<sup>2</sup>°C respectively.

The variation of external convective heat transfer coefficient  $h_{cg}$  on different days for both types of solar stills is shown in figure 2.

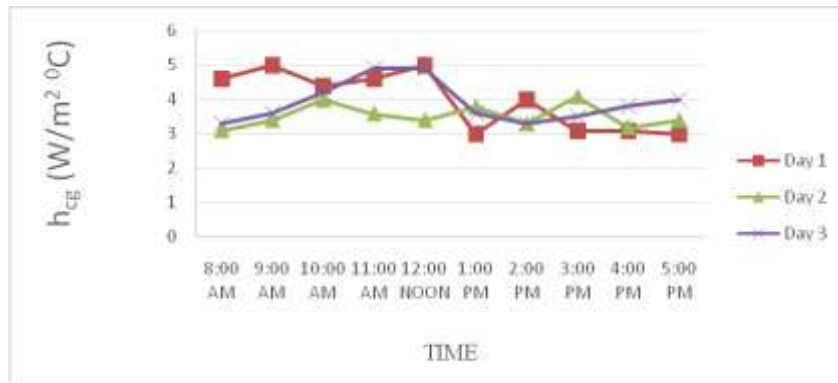


Fig. 2 Variation of  $h_{cg}$  on different days for both types of solar stills

The external convective heat transfer coefficient from outer glass cover to ambient ( $h_{cg}$ ) varies correspondingly with wind speed. The similar variation in  $h_{cg}$  was observed for both conventional and stepped type solar still because the experiments were performed simultaneously on both still and the maximum value of  $h_{cg}$  was evaluated as  $4.9 \text{ W/m}^2\text{ }^\circ\text{C}$ . The variations of external radiative heat transfer coefficient ( $h_{rg}$ ) for conventional and stepped type solar still are shown in figs. 3 to 5.

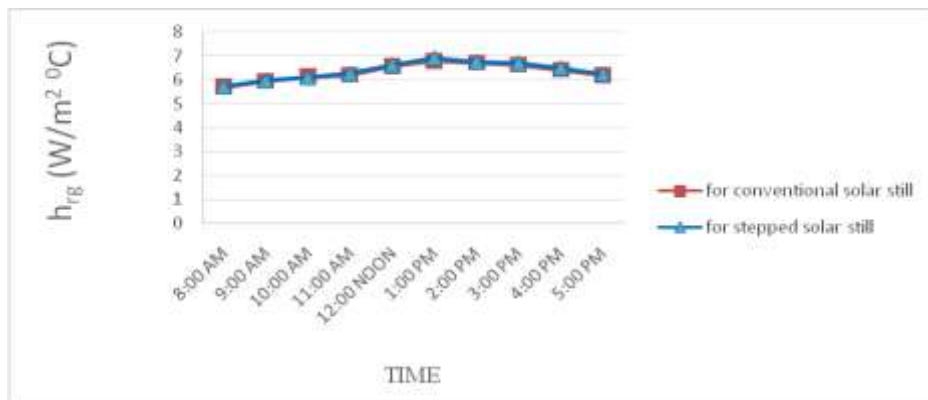


Fig. 3 Variation of  $h_{rg}$  on day 1

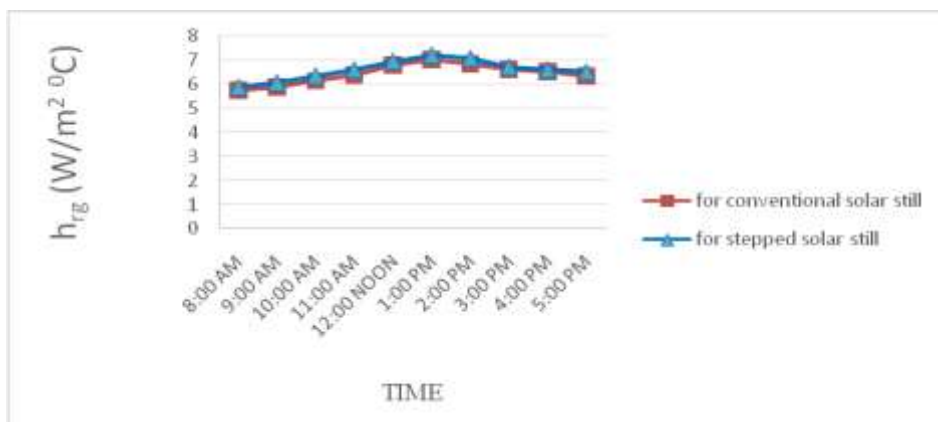
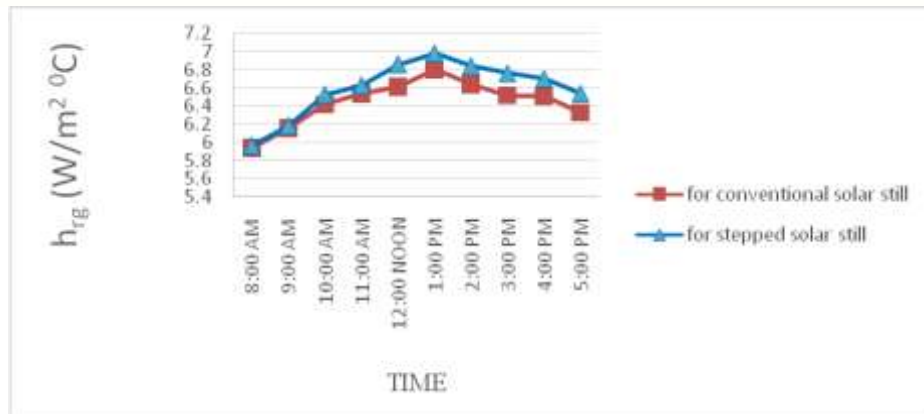


Fig. 4 Variation of  $h_{rg}$  on day 2



**Fig. 5 Variation of  $h_{rg}$  on day 3**

The external radiative heat transfer coefficient ( $h_{rg}$ ) from outer glass cover to ambient changes correspondingly with outer glass cover temperature. Maximum value of  $h_{rg}$  was observed 7.04 and 7.21 W/m<sup>2</sup> °C for conventional and stepped solar still respectively.

#### IV.CONCLUSION

In present work evacuated tube collector solar water heater coupled stepped and conventional solar stills are tested and their thermal performances have been analyzed. The effect of flow rates (50, 75, 100 ml/min) on stepped still has been studied. The water temperature and glass cover temperature was observed to increase with increase in solar intensity and reached maximum about 13:00 p.m. in both solar stills. In conventional and stepped solar stills, maximum water temperatures were observed to be 66.2 °C and 85°C respectively at 13:00 p.m. The temperature of water and inner glass cover was observed considerable higher in stepped type solar still than conventional still. In the conventional solar still, maximum value of  $h_{cw}$ ,  $h_{ew}$  and  $h_{rw}$  was observed 2.53, 15.3 and 7.57 W/m<sup>2</sup> °C respectively. It was found that  $h_{cw}$  was decreased and  $h_{ew}$  was increased with increase in flow rate of feed water in stepped solar still. In the stepped still, the maximum values of internal heat transfer coefficients  $h_{cw}$ ,  $h_{ew}$  and  $h_{rw}$  was observed as 3.40, 30.74, 8.40 W/m<sup>2</sup> °C respectively. The maximum value of external heat transfer coefficient  $h_{rg}$  was observed 7.04 and 7.21 W/m<sup>2</sup> °C for conventional and stepped solar still respectively.

#### Nomenclature

|            |                                                 |
|------------|-------------------------------------------------|
| A          | Area (m <sup>2</sup> )                          |
| c          | Specific heat (J/kg K)                          |
| h          | Heat transfer coefficient (W/m <sup>2</sup> °C) |
| m          | Mass (kg)                                       |
| T          | Temperature (°C)                                |
| P          | Partial pressure (N/m <sup>2</sup> )            |
| $\alpha$   | Absorptivity                                    |
| $\tau$     | Transmissivity                                  |
| $\epsilon$ | Emissivity                                      |

|          |                                                                                 |
|----------|---------------------------------------------------------------------------------|
| V        | Wind velocity (m/sec)                                                           |
| I (t)    | Solar radiation intensity ( $\text{W/m}^2$ )                                    |
| $\sigma$ | Stefan–Boltzmann constant ( $5.6697 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$ ) |
| t        | Time (sec)                                                                      |
| $h_{cw}$ | Internal convective heat transfer coefficient ( $\text{W/m}^2\text{C}$ )        |
| $h_{ew}$ | Evaporative heat transfer coefficient ( $\text{W/m}^2\text{C}$ )                |
| $h_{rw}$ | Internal radiative heat transfer coefficient ( $\text{W/m}^2\text{C}$ )         |
| $h_{cg}$ | External convective heat transfer coefficient ( $\text{W/m}^2\text{C}$ )        |
| $h_{rg}$ | External radiative heat transfer coefficient ( $\text{W/m}^2\text{C}$ )         |

#### **Subscripts**

|     |                |
|-----|----------------|
| g   | Glass cover    |
| w   | Water          |
| a   | Ambient        |
| s   | Sky            |
| p   | Absorber plate |
| c   | Convective     |
| r   | Radiative      |
| e   | Evaporative    |
| eff | Effective      |

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