Development product of a multi-layer solar distillation system connected to tubular solar collectors by using gravel

Muntadher H. Abed¹, Muna S-Kassim², Fouad A. Saleh²
¹Institute of Technology, Middle Technical University, Baghdad, Iraq
²Department of Mechanical Engineering, Mustansiriyah University, Baghdad, Iraq
E-mail: engmuntadher.alsafi1987@gmail.com (Muntadher H. Abed)

Abstract. Solar distillation occurs within a device called the (solar still). There are many types of solar still. In this study, the addition of modern technology for solar still was used. Experimental tests have conducted in (Baghdad), the capital of (Iraq). On the other hand, (MAT LAB) program was used to formulate mathematical formulas. The study was conducted during (July) and (August) and extended during the testing day from (5:30 am) to (10:00 pm). Coarse and fine gravel added to the solar still basins to develop its product. The percentage of increase in the production of solar still with the presence of gravel was (47%), the percentage increase in night productivity was (64%).

Keywords: multi-layer, solar still, tubular collectors, potable water, distillation

Table 1. Symbol List:

| symbol     | The meaning of the symbol                                      | Measuring unit |
|------------|-----------------------------------------------------------------|----------------|
| Qeff       | Rate of thermal energy affecting                                | (watt)         |
| mevi'      | Vaporized water mass rate                                       | (kg/second)    |
| hfgi*      | Latent heat of evaporation (corrected)                          | (j/kg)         |
| hfgi       | Latent heat of evaporation                                      | (j/kg)         |
| cpi        | Thermal capacity of water at each stage                         | (J/kg. K)      |
| cpwa       | Thermal capacity of salty water                                 | (J/kg. K)      |
| Mwai       | Mass of salty water at each stage                               | (kg)           |
| Tswai      | Water surface temperature at each stage                         | (°c)           |
| Tcond i    | The temperature of the condensate at each stage                 | (°c)           |
| dTswai / dt| Rate of time change of water surface temperature                | (°c/ second)   |
| Qlosses, i | The amount of heat lost at each stage                            | (watt)         |
| M prodi    | The amount of potable water produced from each stage            | (kg)           |
| pswai      | Molecular pressure of the water surface at each stage           | (N/m²)         |
| Pcond i    | Molecular pressure of the condenser surface at each stage       | (N/m²)         |
| hswai      | Convection heat transfer coefficient between the water surface  |                 |
|            | and the lower part of the next stage                            | (W/ m². K)     |
| hmi        | Evaporation mass transfer coefficient at each stage             | (W/ m². K)     |
| Asi        | Surface area of the water                                       | (m²)           |
| Twain      | The temperature of the water entering the evaporator            | (°c)           |
| Twaout     | Water temperature outside the evaporator                        | (°c)           |
| Mprod exi  | The amount of experimental potable water at stage               | (kg)           |
| MProd thi  | The amount of theoretical potable water at stage                | (kg)           |
1. Introduction:

Many countries of the world suffer from the problem of scarcity of usable water, despite the proximity of water sources such as the Bays, Seas and oceans. Solar distillation is one of the most important solutions to solve the problem of water scarcity in countries suffering from this problem. This importance was achieved through (economic and long-life, environmentally friendly, using solar energy, renewable and clean energy). The principle of solar distillation is similar to the process of cloud formation and rainfall. The solar radiation falls on the surface of the water inside the still basin. Its temperature rises to evaporate and rises to the top to condense on the underside of the condenser and fall in the form of droplets collected inside the water collecting channel. This process takes place within a device called the (solar still). There are many types of solar stills. The researchers went on to add multiple types of solar stills and work to improve the productivity of solar stills. Researchers have focused on two main types of solar stills: single layer solar still and multi-layer solar still.

The following section has listed the previous researches that the current study was based:

- **Al naser and Karaghouli (2004):**
  Two kinds of solar still studied, one had a single basin and the others contained two basin in the same area. The study has conducted during the months (June - February). It proved that, the highest productivity of potable water was during the month (June), because the height rate of solar radiation was during this month. The study also proved that the yield of the double basin solar still was higher than that of the single basin.

- **Nijmeh. et.al. (2005):**
  Conducted an experimental and theoretical study on the effect of adding natural material substance within abasin of single basin solar still, (charcoal, dissolved salts, and a dye of a violet color). The study was conducted in (Amman) capital of (Jordan), during the months (April and May). It was found that the highest productivity at dissolved salts.

- **Patil et.al. (2014):**
  This study investigated the previous research and determined the factors affecting the production of solar still; these factors were as follows. Factors that improved still productivity were identified and were on two types, first enhancements cover plate of Solar Still which included (Inclination and Direction the cover Plate of Solar Still, Wind speed, Use of Sprinkler at Top of the Solar Still, Cover Temperature, The distance between the water surface and the underside of the condenser). Other factors controlled by solar distillation included (The depth of water inside the still basin, types of energy storing materials, the nature of the materials used within the solar still basin, and use of dye inside solar still).

- **Obaid Younas et.al. (2014):**
  The study added a new type of solar still Multi-layer solar still coupled with Fresnel lens. The study was conducted in (Abu Dhabi, UAE), There was an improvement in the productivity of solar still.

- **Maha (2016):**
  An experimental and theoretical study was conducted on a multi-layer solar still that derived its energy from a solar collector in the form of (parabolic trough collector). The study has conducted in the city of (Kirkuk) in the State of (Iraq). The results of this study showed that the yield of this still was (10-20%) higher than the single layer solar still. The current study involves the addition of a modern technique to the multi-layer solar still. This technique includes linking the solar distillate to an insulated tank. This reservoir, in turn, included (12) tubular solar collectors.

2. Work principle of a multi-layer solar still connected to tubular solar collectors:

This type is classified into solar stills where the solar distillation is indirect. The water was heated inside tubular solar collectors; hot water returned to a thermally insulated tank by the network Pipe, hot water was pumped from the insulated tank into the evaporator. Then the water inside the basin of the first layer acquired heat from the evaporator. A heat exchange occurred between the evaporator and the water surface to warm the water surface then water began to evaporate. The water from the
evaporation was pumped back into the isolated tank. On the other hand, water at each layer drew the necessary heat for evaporation, of steam rising from the previous layer and sequentially.

3. **Description the parts of the solar distillation system:**

3.1 **Tubular solar collectors:**
In this research, twelve tubes made in two layers and a vacuum was between these two layers. It was made from glass, and the inner layer was dyed black to maximize absorption of solar radiation. The tubes are with the following dimensions (length 180 cm, inner diameter 4.5 cm, outer diameter 6 cm). All these tubes were connected to an isolated cylindrical tank with a capacity of (80 liters). The tank filled with pure water, to eliminate the accumulation of salts inside the tank because the cycle was closed.

3.2 **Multi-layer solar still:**
In this study, four layers of solar still were used. It made from galvanized iron in the form of parallel rectangular surfaces. The dimensions of the basins were 120 cm in length, and 40 cm in wide. The height of the first layer was 16 cm, and 12 cm for the others layers. Evaporator was a heat exchanger made from copper and installed inside the basin of the first layer. The upper surface of the basin for each layer was covered with condenser. The condenser was made from galvanized iron in the form of (V) with an angle of (165°). The water collector installed inside each stage. It used in the form of a channel for the collection of potable water made of heat resistant (pvc) material.

3.3 **Hot water pump:**
A special pump for solar energy research was used in this research. The flow rate designed for six flow rates. The flow rate of the pump has been fixed and calibrated at (3.25 liters per minute).

3.4 **Feeding tank:**
The feeding tank made in the form of a cube with a side length (45cm), the tank connected to a network of (4 mm diameter) thin pipes. The purpose of the feeding tank was to ensure the survival of the water height within the basin of each stage.

[Figure 1. solar distillation system]
4. Measuring devices:
Ten thermocouples type (k) were used to measure the temperature of the water surface and the temperature of condensation. Eight of them were installed so that at each stage two were established, one touching the water surface and the other measuring the surface temperature of the condenser. Two thermocouples also used to measure the temperature of the water inside and outside the evaporator. All the thermocouples have connected to the data logger. A solar meter was used to measure the intensity of solar radiation. Thermometer also used to measure ambient air temperature. Water cylinder used to calculate the amount of water produced by each layer.

![Solar meter](Image)
![Data logger](Image)
![Thermometer](Image)
![Water cylinder](Image)

Figure 2. Measuring devices

5. Experimental testing:
Experimental tests have conducted in (Baghdad), capital of (Iraq). Which were located at latitude (33.41º) and longitude (44.42º).

5.1. Cases taken:
- **First case:**
  In this research, the basic case that adopted was when the basins were empty and contained only water. The productivity of this case compared to that of previous studies and there was a clear superiority in productivity.
- **Second case:**
  In this case, gravel added to the basins of the three stages, Add coarse gravel inside the first basin. Fine gravel added to the second and third basins.
6. Boundary conditions:
There are two conditions influencing

- Climate conditions:
  Which were factors of the atmosphere surrounding the test site and these factors cannot be controlled and can be explained through the table (2)

| Nu of case | Nature of climate | Air Humidity (%) | Wind Speed (Km/hr) | Ta Max (°C) | Ta Min (°C) | Is Max (W/M²) |
|------------|-------------------|------------------|-------------------|-------------|-------------|---------------|
| Case1 27/7/2018 | Sunny | (11-29%) | (16-36) | 44.6 | 30.6 | 1117 |
| Case2 30/7/2018 | Sunny | (13-31%) | (14-34) | 46 | 29.5 | 1165 |

- Operational conditions:
  Were the factors that depend on the operation of the solar still. Were installed based on previous studies. As shown in the table (3).
Table 3. Operational conditions

| Nu of stage | Height of water (cm) | Length of basin (cm) | Width of basin (cm) | Mass of water (kg) |
|-------------|---------------------|----------------------|---------------------|-------------------|
| Stage 1     | 4                   | 120                  | 40                  | 19                |
| Stage 2     | 2.5                 | 120                  | 40                  | 12                |
| Stage 3     | 2.5                 | 120                  | 40                  | 12                |
| Stage 4     | 2.5                 | 120                  | 40                  | 12                |

7. Experimental steps:
   Experimental steps were divided into two parts
   - Experimental steps that precede the working day:
     1. Design and manufacture parts of the solar distillation system and transfer them to the test site.
     2. The tubular solar collectors were fixed and connected to the insulated tank
     3. At the first stage of the solar still, installed the basin and calibrated it with the ground to maintain the level of water inside it.
     4. The evaporator installed inside the first stage basin and connected to the isolated tank on one side and outside of the basin connected to the pump.
     5. The pipeline connected between the feeding tank and the first stage basin by a raft to get the desired height.
     6. The water collection channel installed at a height of (10 cm) from the bottom of the basin in order to collect and extract the water from one side of the basin.
     7. The condenser installed as a cover over the first stage basin
     8. Two thermocouples installed. One touching the surface of the water and the other touching the surface of the condenser.
     9. The second stage basin installed above the first stage basin by
    10. Steps 5 to 9 have repeated with each stage.
    11. Two thermocouples installed one when water enters the evaporator and the other when exiting.
   - Experimental Steps on the test day:
     The test was run from (5:30 am) to (10:00 pm). The experimental steps can be summarized as follows.
     1. Connected all the thermocouples to the Data Logger.
     2. All measuring devices have been configured.
     3. The valve of water supply opened from the insulated tank to the evaporator.
     4. The hot water pump has plugged with electricity and operation.
     5. The water return opened from the evaporator to the insulated tank valve.
     6. The water supply valves opened from the feeding tank to the solar still basins.
     7. Readings have taken every half hour.
     8. At (10:00 pm) all the valves have closed and the pump has disconnected from the electricity.
     9. The basins have emptied and cleaned after each case to get rid of the salts and the tubular solar collectors have washed.

8. Theoretical calculations and computer software:
   In this study, (Mat lab) was used to carry out theoretical calculations and there several hypotheses at the beginning of the design, the most important of which:
   1. The mass of drinking water produced should equal the mass of the condensate water.
   2. The resulting water temperature should be equal to the water temperature at the condenser surface.
   3. The surface area of water within the four basins should be equal for both cases.
   4. The slight difference in radiation intensity ignored for both cases.
   5. Water physical properties have matched for inside the solar still and the resulting water.
8.1. Energy and Mass conservation equations:
The governing equations can be formulated based on energy and mass conservation equations for each layer of the solar still and the following form [5]:

- **First layer**
  \[
  Q_{eff} - m_{ev1} \cdot (h_{fg1}^* + c_p \cdot T_{cond1}) = M_{Wa1} \cdot c_{pwa} \cdot dT_{swa1} / dt + Q_{loss1}
  \]

- **Second layer**
  \[
  m_{ev1} \cdot h_{fg1}^* - m_{ev2} \cdot (h_{fg2}^* + c_p \cdot T_{cond2}) = M_{Wa2} \cdot c_{pwa} \cdot dT_{swa2} / dt + Q_{loss2}
  \]

- **Third layer**
  \[
  m_{ev2} \cdot h_{fg2}^* - m_{ev3} \cdot (h_{fg3}^* + c_p \cdot T_{cond3}) = M_{Wa3} \cdot c_{pwa} \cdot dT_{swa3} / dt + Q_{loss3}
  \]

- **Fourth layer**
  \[
  m_{ev3} \cdot h_{fg3}^* - m_{ev4} \cdot (h_{fg4}^* + c_p \cdot T_{cond4}) = M_{Wa4} \cdot c_{pwa} \cdot dT_{swa4} / dt + Q_{losses4}
  \]

8.2. Condensation temperatures for the four stages:
The condensate surface temperatures of the four stages can be calculated using the following equations: [5]

\[
T_{cond1} = T_{swa1} - 2
\]
\[
T_{cond2} = T_{swa2} - 2.7
\]
\[
T_{cond3} = T_{swa3} - 1.11
\]
\[
T_{cond4} = T_{swa4} - (0.00007 \cdot T_{swa4}^2) + (0.015 \cdot T_{swa4}^2) - (0.976 \cdot T_{swa4}) + 10.324
\]

8.3. The amount of thermal energy affecting:
The amount of heat entering the solar still is the main source of the solar distillation process that can be calculated by the equation: [6]

\[
Q_{eff} = m_{evtotal} \cdot c_{pwa} \cdot (T_{wa1} - T_{waout})
\]

8.4. Latent heat of evaporation:
Can be calculated by the following equation: [6]

\[
h_{fgi} = 1000 \cdot (3161.5_{(Tswai)} - (2.40741 \cdot T_{swa}))
\]
The amount of latent heat is corrected by the following equation:
\[
\frac{hfg_i^*}{\text{mg}} = hfg_i + (0.68 \times cpi \times (Tswai - Tcond))
\]
(11)

8.5. Thermal capacity of water:
Can be calculated through the following equation [7]
\[
\text{Cpi} = 100 \times [4.2101 - (0.0022 \times Tswai + (5 \times 10 - 5 \times Tswai^2) - (3 \times 10 - 7 \times Tswai^3)]
\]
(12)

8.6. Pressure of water molecules when evaporation and condensation:
The evaporation pressure of the water surface molecules of the four phases can be calculated by the following equation. [8]
\[
pswai = e^{(25.317 - \frac{5144}{Tswai})}
\]
(13)
The pressure of the water molecules at the surface of the condenser can be calculated by the following equation.
\[
Pcondi = e^{(25.317 - \frac{5144}{Tcondi})}
\]
(14)

8.7. Convection coefficient of water surface:
Calculated by the following equation [9]
\[
\text{hswai} = 0.884 \times \left[ (Tswai - Tcol) + \frac{Tswai \times (pswai - pcondi)}{268.9 \times 1000 - pswai} \right]^{\frac{1}{2}}
\]
(15)

8.8. Mass transfer coefficient:
It is calculated by equation: [10]
\[
\text{hmi} = 16.273 \times 0.001 \times \text{hswai} \times \frac{(pswai - pcondi)}{(Tswai - Tcondi)}
\]
(16)

8.9. Quantity of evaporated water:
It is calculated by equation
\[
\text{mevi} = (Tswai - Tcondi) \times \text{hmi} \times \frac{Asi}{hfg_i^*}
\]
(17)
Asi: The surface area of water inside the basins in the four layers was a fixed amount (0.48m²).

8.10. Mass of water produced:
Calculated by the following equation
\[
\text{Mprodi} = \text{mevi} \times dt
\]
(18)
D = (30minutes).
The program was run at the beginning more than once and found that the error ratio between experimental and theoretical productivity was less than (12%).
9. Results:

9.1. Comparison of water surface temperature for both cases:

The results will be discussed in a way that the water surface temperature behaves with time for both cases first and then discuss the difference between the two cases for all layers.

- **First layer:**
  A sudden rise in the temperature of the water surface of the first layer of both cases was due to the pre-heating of the water inside the isolated tank before the day of the experimental test. Then the temperature of the water surface began to decrease due to the heat exchange between the water supplied and the water inside the basin of this layer and the other hand heat exchange between water within the isolated tank and the water returned to the tank. It was observed at (9:30 am) the temperature of the surface of the water in this layer began to rise again, and that was explained by the high temperature of the water supplied by the isolated tank because of the investment of solar energy by the solar collectors tubular. The temperature continued to rise until it reached (5:00 pm), after which it began to decline due to the decay of solar energy invested. After (5:00 pm) the surface temperature of the water began to decrease to the end of operation at (10:00 pm). The difference between the first and second case in this layer was the noticeable rise in temperature of the first layer of the second case than in the first case and the reason for the presence of gravel inside the basin. The difference in temperature during the operation period was due to the thermal storage and thermal conductivity of the gravel.

- **Second layer:**
  The temperature of the surface of the water was gradually increased from the beginning of the operation to reach the highest level between (4:00 and 5:00 pm). That was due to the thermal energy received from the rising water vapor from the first layer. Then the temperature began to decrease to the end of the operation. The difference between the first and second case in this layer was the amount of heat received for this layer in the second case was much higher than the amount of heat received in the first case and the reason due to the warming temperature of the surface of the first layer of the second case.

- **Third layer:**
  The temperature of the surface of the water in this layer was increased from the beginning of the operation until reached (5:00 pm) after it began to decrease. There was a clear superiority of the
temperature of this layer in the second case on the first case the reason was due to the amount of high heat received from the first layer in this case and on the other hand the presence of gravel in the basin.

- **Fourth layer:**
The calculations of this layer have been neglected because of their low theoretical and practical productivity.

9.2 *Comparison of overall productivity of both cases:*

- **First layer:**
  It was noted that the productivity of this layer, for both cases, was the highest possible at the beginning of the operation explained by two reasons. First, due to the high temperature of the water surface at the beginning of the operation and the second returned to the low temperature of the condenser surface. The greater the thermal difference between the water surface and the condensate surface led to increased productivity. The difference in the productivity of this layer
for both cases was evident throughout the operating period. It was also observed that the night productivity of the first layer in the second case on the productivity of the same layer in the first case that was due to the thermal storage of gravel.

- **Second layer:**
  It was observed that the productivity of this layer for the second case exceeded the productivity of the same layer in the first case. This is to the amount of heat received were higher, the presence of gravel in the basin of this layer, and the thermal difference between the water surface and the bottom surface of the condenser was high. After 8:00am, the productivity of this layer, for both cases, began to increase. It has noted that in some cases there was predominance in the productivity of this layer in the first case on the same layer of the second case. This can be explained by the fact that despite the rise in water surface temperature of this layer in the second case. However, the temperature of the surface of the condenser was also high because of the presence of gravel in the third layer. This led to a low thermal difference in the water surface and the condenser surface, which causes a decrease in productivity.

- **Third layer:**
  It has been noted that the productivity of this layer, for the second case, was higher than its counterpart in the first case. This is throughout the period of operation due to the presence of gravel in the basin of the second case as well as the heat difference between the high surfaces temperatures of the water and the condenser.

9.3 **Comparison in terms of night productivity for both cases:**
Night productivity is the productivity that occurs during the period from the absence of the sun until (10:00 pm).

![Figure 8. night productivity (kg)](image)

The presence of gravel and its thermal storage capacity made the night productivity of the second case overcome the first case by (63%).

10. **Conclusion:**
Practical tests were conducted in Baghdad capital of Iraq for two cases. The advantage and results of the system can be summarized in the following points.
1. When operating the system, the basins were empty. The rate of improvement in the productivity of another multi-stage solar still which depends on other sources of heating, reached about (40%).
2. Preheating before the test day of the water inside the isolated tank gave an increase in productivity at the beginning of the test estimated at (13%) of total productivity.
3. It surpassed other types of solar distillates in terms of night productivity. The night output lasted three hours after sunset.
4. The total productivity of this type of solar distillates has improved by adding soft and rough gravel to the basins. The rate of increase in productivity (47%).
5. The addition of gravel to the basins increased the night productivity by (64%).
6. Total productivity reached the addition of gravel (8.3 kg/m².day). This productivity is higher than that of multi-layer solar still.
7. The percentage of Hardness in water used was (425 mg/L) but when gravel used the percentage of Hardness was (98 mg/L).

References
[1] Karaghouli A A and Naser WE 2004 Performances of single and double basin solar stills Applied Energy 78 347-354.
[2] Akash B, Nijmeh M S, Odeh M S 2005 Experimental and theoretical study of a single – basin solar still in Jordan International Communication in Heat and Mass Transfer 32 565-572.
[3] Patel P, Solanki A S, Soni U R and Patel A R 2014 A review to increase the performance of solar still make it Multi-layer International Journal Recent and Innovation Trends in computing and communication 2 173-177.
[4] Obaid y, Fawzi B and Didarul I 2015 Seasonal behavior and techno economic analysis of a multi-stage solar still coupled with a point-focus Fresnel lens Desalination and Water Treatment 1944 1-14.
[5] Maha R R. 2016 Enhancement the Performance of Passive Multi Stages Solar Still by using Parabolic Trough Collector M.Sc. Thesis, Tikrit University.
[6] Mahmoud I M S, 2008 New and renewable energy and environmental engineering M.S.C Thesis, Durham University 64-65.
[7] Frank P I, David P D, Theodre L B, Adrienne S L 2007 Fundamental Of Heat and Mass Transfer Sixth Edition, John Wiley and Sons,United States of America.
[8] Eames I W, Maidment G G and Lalzad A K 2007 A theoretical and experimental investigation of a small-scale solar – powered barometric desalination system Applied Thermal Engineering 27 1951-1959.
[9] Mahmoud I M, Shatat K M 2010 Determination of rational design parameters of a multi-stage solar water desalination still using transient mathematical modeling Renewable Energy 35 52-61.
[10] Fernandez J and Chargoy N 1990 Multi-stage, indirectly heated solar still Solar Energy 44 215-223.