Experimental Investigation and Simulation of Convective Heat Transfer in a Solar Still

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Abstract. This paper mainly focuses on the design of a water distillation solar still that can purify and desalinate water from any source in an affordable, portable and sustainable manner. It attempts to efficiently produce clear water by solar energy conversion. Since, low productivity is of the limitation of the usage of such stills, this paper makes an attempt to evaluate the heat transfer coefficient of single slope basin type solar still by Simulation Analysis and checking the optimum conditions. A design prototype was constructed by studying the optimized configurations from various researchers. After carrying on the experiments, the effect of various parameters was evaluated. The parameters identified include temperatures, properties of inlet water, wind velocity and relative humidity. Simulation results were then compared to the experimental results at the obtained optimum conditions.

Nomenclature

\( C_p \) Specific Heat Capacity, J/kg\(^0\) C
\( h \) Heat Transfer Coefficient, W/m\(^2\) °C
\( k \) Thermal Conductivity, W/m\(^0\) C
\( L \) Characteristic Length, m
\( \dot{m} \) Mass flow rate, kg/s
\( Pr \) Prandlt Number
\( Re \) Reynold’s Number
\( T_{vap} \) Vapor Temperature, \(^0\) C
\( T_{water} \) Water Temperature, \(^0\) C
\( T_{glass} \) Glass Temperature, \(^0\) C
\( T_{air} \) Ambient Air Temperature, \(^0\) C
\( u \) Velocity, m/s
\( V_{air} \) Local Wind Velocity, m/s
1. Introduction
Clean air and potable pure drinking water are the two most essential requirements of life. A major part of the earth does not have access to pure drinking water. The increasing lack of useable water is one of the most essential issues in various nations. Meeting this increasing demand of pure potable water in a safe and sustainable method is a hard slog to achieve. Utilizing water for survival from sources like the wells, rainwater, river, or lake water can lead to numerous water borne diseases, which in turn results in the death of millions each year. Solar Distillation serves this aim well. It is a potentially good method for water purification and requires solar energy for its operation which is eco-friendly and free.

2. Literature survey

2.1. Desalination in UAE
Water is the basis of most processes happening on this planet. These days, we are reliant on rich and continuous supply of water for living and working. UAE being a water scarce country, with the continuous discharge of highly saline/brine water and continuously depleting natural water resources has to depend heavily on desalination. 98% of our potable water supply comes from desalination. 1/3rd of our comprehensive water supply also comes from desalination. Around 50-70% of the total cost of desalination process is the cost of energy alone. The main challenge here is an extremely high cost process and also harm to the environment. How do we fulfil this colossal demand of pure water in an eco-friendly way? Hence Solar Distillation is a solution to address these challenges, as it is the most sustainable technique being investigated today.

2.2. Solar stills
Solar Distillation is the relatively simple yet effective treatment of brackish water supplies. Equipment called Solar Still utilizes the solar energy to warm salty/impure water to the extent of evaporation. As soon as the water evaporates, its vapours rise, then condensing on the surface of the glass. This process eliminates all the contaminating elements, such as, the salts and various other metals. Moreover, it disposes off microbiological life forms too. The final product is pure water, cleaner than rainwater.

Stills can especially be used in those areas where there is a recurring need for desalinating the water and where large amount of oil/fuel is used to generate energy for desalination. This provides a renewable energy plant, in turn being eco-friendly.

2.3. History & Research Gap
Researchers have conducted studies on the simple solar still because of its simple design and construction; low initial investment cost and operational costs and easy maintenance. But numerous developments to this basic design have been studied due to its poor efficiency. Various experimental as well numerical analyses have been conducted by various researchers on several configurations of Basin Type Solar Stills by modifying various parameters related to its performance.

2.3.1. Cover tilt angle. Contradicting inferences were observed regarding the impact of cover tilt angle on the efficiency and yield of the still. Dwivedi and Tiwari [1] found that the most favorable angle of inclination of the glass-cover for both single and double slope stills is 15° and it is made up of plane glass of 4mm thickness. Tabrizi and Sharak [2] built a solar still with a cover inclination angle of 45° for their investigation, which was a model integrated with a sandy reservoir.

Khalifa and Hamood [3] derived a correlation by optimizing the results of various investigators. The obtained correlation illustrated that the productivity of the still can be affected by the inclination alone by
up to 63% by the water depth only by up to 33%. Their correlation shows that a cover tilt angle of 30° gives the maximum yield.

2.3.2. Solar intensity. Solar radiation is a factor which has a maximum influence on the productivity as it is responsible for providing all the energy that is required for water evaporation. Dwivedi and Tiwari [1] measured solar intensity using a solarimeter, with a least count of 2W/m2. Khalifa and Hamood [3] obtained a correlation by fitting a 2nd order polynomial by regression. It clearly illustrates that the still’s yield is a function of solar intensity.

2.3.3. Wind velocity. The influence of wind velocity over the productivity of the solar still was examined by El-Sebaii [4] using various software simulations. An ideal depth of the basin water was specified beyond which the yield enhances along with the increment in the wind velocity.

2.3.4. Other studies. Numerous experimental and numerical analyses were carried out on various types of solar stills so as to achieve an ideal strategy by looking at the impact of various parameters or the factors on the still’s performance.

The essential parameters examined in this process were: cover tilt angle, solar radiation and also the water depth along with dark dyes used for increase absorptivity. It can also be influenced by adding dark dye up to 20% and by the insulation thickness the solar radiations that are received on the still.

Dwivedi and Tiwari [1] assessed the heat transfer coefficient of passive solar stills. They found that the rise in water depth from 0.01 m to 0.03 m shows a negligible deviation in evaporative and convective heat transfer coefficients. The yearly productivity diminishes with the upsurge of water depth.

Mousa Abu-Arabi et al [5] explored the modelling and performance evaluation on a solar still (basin type) with the salty water streaming in-between a double-glass. This was done so as to reduce the temperature of the glass and in turn enhance the water-to-glass temperature variance by insulation, since the comparative performance of the stills relies on the level of insulation used. For completely insulated stills the double glass is superior when the losses surpass a limit.

R. Alvarado-Juárez et al [6] displayed their outcomes as Streamlines, isotherms, iso-concentration of water, and condensate of water as well as the Nusselt and Sherwood numbers. It likewise demonstrated that the water condensate surges as soon as the angle of inclination is increased (15° ≤ θ ≤ 35°). The upper limit of distilled water occurs for a one-cell structure of θ = 30° and A = 10 and 6.67.

The objective of this paper is to bridge in the gap in obtaining a sustainable route for purification and desalination of water. A monitoring scheme has been developed which can study the routes to decide which approach is the most suitable, considering preliminary investment and operational costs, consistency of system, and efficiency of the still.

3. Heat Transfer in Solar Stills

Many scholars have undertaken various researches on the Simple single slope type solar still due to its easy design, easy maintenance as well as low initial investment and operating costs. But due to its poor efficiency, high heat transfer losses, numerous advancements have been suggested and studied. Two types of heat transfer occur in a Solar Still, as discussed below.

3.1. External heat transfer

Heat Transfer taking place externally occurs due to the following factors which are independent of each other, and thus indirectly affect the performance of the Still:

- Conduction
- Convection
- Radiation

3.2. Internal heat transfer
Heat transfer taking place inside the Solar Still is the major cause of distillation of saline water. This is known as Internal Heat Transfer, and it occurs due to: Convection, Evaporation, and Radiation.

3.2.1. **Convective Heat Transfer.** The difference in the density of the humid air is the major cause of Convective Heat transfer occurring inside a solar still.

3.2.2. **Evaporative Heat Transfer.** The Heat of the sun (solar radiation) leads to the Evaporative Heat transfer inside a solar still. And the difference in the temperature of the glass and water leads to the condensation of Water.

3.2.3. **Radiative Heat Transfer.** There are 3 factors that can influence the Radiative Heat transfer occurring inside a solar still, Reflectance, Absorbance, and Transmittance. A major factor affecting level of production of the solar still is the quantity of solar radiation coming on the glass top. Other parameters radiation depends on are:

- Intensity;
- Incident Angle;
- Optical properties of the material;
- Solid angle defined by the bundle of rays;
- Temperature.

3.3. **Phase Change**
Thermodynamic properties of water being evaporated influence the performance of the still which help us evaluate the losses occurring in it during its working.

3.4. **Losses**
Large quantities of solar energy are transmitted by the glass top, but not all of those radiations are used for evaporation of water in the basin. A minimal amount of it gets absorbed and reflected too, by the basin surface, water and glass top.

The energy absorbed after conduction through the vapours is convected to the surface of glass top or by the evaporation taking place inside the still. The top is noticeably transparent to radiation of the sun and opaque to the IR radiations. Heat is then transferred from glass top to the surroundings; by convection to the surrounding air and also the by radiations to the clouds. Hence it leads to various losses.

4. **Experimental Parameters**
This research tests the suggested potential interventions to increase yield and the efficiency of the simple Solar Still (basin type). This is done by designing a complete Simple solar still, analysing different parameters influencing its productivity and undertaking Numerical analysis of its convective heat transfer.

4.1. **Cover tilt angle**
The still was designed with a glass cover tilt angle at 30°, since the literature shows highest productivity at a tilt angel of 30°.

4.2. **Temperature**
The following temperatures were measured.

- Water temperature
- Vapor temperature
- Glass temperature
- Ambient air temperature

Temperatures of water, water vapor and also the glass cover were recorded using a digital temperature and Humidity meter. The ambient temperature was recorded by a thermometer.

4.3. **Wind velocity**
4.4. **Distillate output**
4.5. Constituents of water

4.6. Humidity

5. Design of experimental set-up

For conducting the experiment, single-slope basin solar still was designed and fabricated. The schematic drawing of single slope still is shown in Fig. 1. Its basin is made up of aluminium, which also provides thermal insulation to the basin. The inclination of the condensing cover for the still is 30°, made up of glass having 6mm thickness. The glass was positioned on the basin of still. A passage is provided at the lower end to collect the yield of solar still through an aluminium tray. For inlet of the water into the still, a pipe with a knob is given at the rear wall of the still.

Holes are also provided in its body to fix thermocouples for measuring temperatures. Other parameters were measured as discussed in above. Photographs of Experimental Solar Still (Front and side view respectively) are shown in Figure 2 and Figure 3.

### Figure 1. Schematic Side view Diagram of the Experimental Set-Up

#### 5.1. Basic Design

- The basin area of the still – 1 m²
- Body: Insulation of basin side surfaces by Aluminium of 3mm thickness (thermal conductivity of 237 W/m K)
- The glass cover: Plane glass (6mm thickness)
- Inlet Duct: Contrived for the inlet of the salty water for conducting the experiment.
- Distillate duct: To accumulate the purified water.

### Figure 2. Photograph of the Experimental Still (Front view)

### Figure 3. Photograph of the Experimental Still (Side view)
5.2. Measured Properties
- Temperatures at various parts of the still
- Local wind velocity
- Relative Humidity
- The amount of distilled water
- The properties of distilled water

5.3. Assembling
Manufacture of the complete still requires various workshop activities like welding, glass cutting, sealing and drilling. All of this can be done with machines like lathe, drill, welding, milling, etc. Various steps involved are:
- Fabricate the outer box with the mentioned material.
- Collector holes and other holes for sensors were made at the time of fabrication.
- Collector tubes were attached to the basin.
- The glass top made (the tilt glass and the vertical glass) is attached/assembled over the basin. The holes on it are also made beforehand.
- This whole still is placed on bricks to provide elevation for the collection of distillate

6. Experiment

6.1. Methodology
The experiments were performed on the set-up. Water (85 L) was led to flow into the basin and left undisturbed. After 24 hours, ambient air temperature, glass temperature, water and vapour temperature and the relative humidity inside the still were recorded throughout the day (8:30am to 4:00pm, hourly). Variations in the wind velocity were also recorded. This was repeated the next day. Hourly variations of all above mentioned parameters are shown below.

| Time (hours) | $T_{up}$ ($^\circ$C) | $T_{water}$ ($^\circ$C) | $T_{glass}$ ($^\circ$C) | Relative Humidity | $T_{air}$ ($^\circ$C) | $V_{air}$ (m/s) |
|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------------|
|              | $T_{water}$ ($^\circ$C) | $T_{glass}$ ($^\circ$C) | Water | Vapor | |
| 8:30         | 34.9            | 33.1            | 36   | 15    | 14    | 36            | 2             |
| 9:30         | 38              | 38.9            | 41   | 16    | 17    | 32.1          | 3.3           |
| 10:30        | 40.6            | 41.9            | 44   | 10    | 10    | 40.8          | 2             |
| 11:30        | 41.9            | 43.3            | 45   | 10    | 10    | 44.8          | 2.5           |
| 12:15        | 39.7            | 44.3            | 46   | 10    | 10    | 49            | 2.9           |
| 13:00        | 44.1            | 46.1            | 45   | 10    | 10    | 53.1          | 2.4           |
| 13:30        | 46.2            | 48.8            | 44.8 | 10    | 10    | 53.1          | 2.4           |
| 14:00        | 50.5            | 52.7            | 44.5 | 10    | 10    | 49.7          | 2.7           |
| 14:30        | 46.2            | 54.4            | 42   | 10    | 10    | 48.4          | 2             |
| 15:00        | 47.2            | 49.9            | 44   | 10    | 10    | 47            | 2.6           |
| 15:30        | 42.7            | 44.3            | 42   | 10    | 12    | 45.2          | 1.6           |
| 16:00        | 43.2            | 43.7            | 40   | 12    | 14    | 43.4          | 0.6           |
Table 2. Various measured parameters for single slope solar still on 15th of May 2017

| Time (hours) | T\text{\_}\text{\_}vap (°C) | T\text{\_}\text{\_}water (°C) | T\text{\_}\text{\_}glass (°C) | Relative Humidity (%) | T\text{\_}\text{\_}air (°C) | V\text{\_}\text{\_}air (m/s) |
|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 8:30         | 30.4            | 35              | 30.8            | 27              | 27              | 32.2            | 2.1             |
| 9:30         | 36.2            | 42              | 37.1            | 24              | 22              | 36.6            | 3.4             |
| 10:30        | 40.5            | 45.5            | 40              | 17              | 16              | 39.3            | 2.9             |
| 11:30        | 51.9            | 53.4            | 42.8            | 10              | 10              | 43.5            | 3.1             |
| 12:30        | 45.5            | 57              | 42.7            | 12              | 15              | 51.6            | 3.5             |
| 13:30        | 44.9            | 55              | 41.4            | 13              | 14              | 49.6            | 3.4             |
| 14:30        | 43.5            | 54.5            | 42.7            | 15              | 16              | 48              | 2.5             |
| 15:30        | 44.9            | 43              | 41.4            | 13              | 14              | 43.8            | 2.7             |

6.2. Initialization

The following Assumptions were made before applying a model:

- The properties such as viscosity, density, thermal conductivity and specific heat capacity are taken at a mean water temperature (Mean T\text{\_}\text{\_}water) of the day.
- The Set\-up is assumed to be completely insulated, with no extra loss of energy.
- The depth of water inside the basin is 0.1m (10cm)

Sieder-Tate Equation for turbulent region (Re > 4000) is used to find the heat transfer coefficient.

(a) Day 1:
Mean T\text{\_}\text{\_}water = 45° C

The properties of the water used in this study are: ρ=990 kg/m³, μ=0.0006 Pa.s, k=0.637 W/m° C and C\_p=4.1795 J/kg ° C.

Re = 14313.75 (Turbulent Region)
Pr = 0.0039
Nu = 7.7872

From Sieder-Tate equation, h = 19.8418 W/m² ° C

(b) Day 2:
Mean T\text{\_}\text{\_}water = 48.175° C

The properties of water used in this study are: ρ=988.76 kg/m³, μ=0.000567 Pa.s, k=0.641 W/m° C and C\_p=4.1802 J/kg ° C.

Re = 15123.05
Pr = 0.0037
Nu = 7.9965

From Sieder-Tate equation, h = 20.5029 W/m² ° C

6.3. Results and discussion
Figure 4 and Figure 5 show the temperature variations of still elements i.e. vapour, water, glass and ambient air against the operating time, on both the days in May 2017 respectively. Glass temperature is observed to shoot up with increasing ambient air temperature.

The variation in wind velocity in these two days is shown in Figure 6. This shows that wind velocity has negligible effect on the yield of the still. The wind velocity decreases the glass temperature, in-turn enhancing the rate of condensation.

Figure 7 and 8 show the Relative Humidity % (of vapour and water*). *Note: RH% of water implies the Humidity near the vaporising water surface, while vapour humidity implies the humidity in the still.
The results of the preliminary tests on the obtained clear distillate (Figure 9) are shown in Table 3. The pH~7 and conductivity~130μS/cm clearly states that the obtained water is fit for domestic use. While the only need observed is to increase the productivity per day.

**Table 3.** Various measured parameters of the distillate from the single slope solar still

| Parameter                  | Day 1  | Day 2  |
|----------------------------|--------|--------|
| $T_{\text{water}}$ (°C)    | 51.1   | 46.9   |
| pH                         | 8.12   | 6.96   |
| Conductivity (μS/cm)       | 419    | 129    |
| Volume Collected (L)       | 2      | 1.8    |
| Time (hrs)                 | 35     | 40     |

7. **Modelling and Simulation**

A 3-dimensional multiphase model of solar still was made for heat transfer in ANSYS Fluent. Computational Fluid Dynamics (CFD) is one of the branches of Engineering, Finding numerical solutions...
of governing equations, using high-speed digital computers. ANSYS Fluent is simulation software based on CFD technique. Various parameters were varied, to check the optimum design required to attain maximum output.

7.1. Geometry and meshing
A 3-dimensional geometry of the solar still was modelled in Auto CAD 2018 as in the experimental set up. This model was then imported into ANSYS 18.2 Workbench Geometry. The model was then meshed using hexagonal meshing of 76212 elements at a growth rate of 1.2, in ANSYS Workbench Meshing.

7.2. Boundary Conditions
As mentioned above, 3 factors that can influence the Radiative Heat transfer occurring inside a solar still, Incidence, Absorbance and Transmittance. A major factor affecting level of production of the solar still is the quantity of solar radiation incident on the glass top, due to transmittance and absorbance, then it is absorbed by the basin.

The simulation was carried out in transient state for comparison of the results with experimental data. The climatic conditions were taken of Dubai (25.1314° N, 55.4196° E). Discrete transfer radiation model was selected, while the solar radiation was calculated using the solar calculator at the given latitude and longitude, from the date and time of the experiment. The simulation had a runtime of around 6 hours because of the number of steps and computer time restrictions. The experiment was carried out from 0830 hours till 1730 hours. During each hour, temperature was being set.

7.3. Initialization
ANSYS Fluent 18.2 was used to convert the equations into numerically solvable algebraic equations, with following assumptions:
- Thermo-physical properties of aluminium, glass, and air remain constant during process.
- Solar still wall temperature is assumed to be constant at all times.

8. Results

8.1. Trends
The following figures show the temperature of the water and the vapor inside the still and the basin, resulting from both Experiments as well as Simulation.
After comparison with the Experimental Data, it is evident that the results do not match exactly, but follow a similar pattern. The similar pattern resulted in an offset of around $20^\circ$ C in the temperature. This surprising behaviour of trends in experiments versus the simulation is most possibly due to the variation in the solar radiations intensity. The solar radiations in simulation don’t take into account the natural offset. They only consider the location coordinates to get the solar intensity, which is an average throughout the year.

The efficiency of the solar still was also calculated using the Heat transfer Coefficient and Vapour temperatures. It was witnessed to be 29%, which has increased as compared to 19% previously. As intensity of solar radiations increases, the efficiency of the still also increases.

8.2. Base as pure black surface
After keeping the base as a black surface during the simulation, the efficiency of the solar still was also found to increase to 48%. Black surface increases the intensity of solar radiations, thus increasing the efficiency of the still.

9. Conclusions
A 1m$^2$ Basin-type simple Solar Still with a plane glass at a tilt angle of $30^\circ$ and an aluminium base was designed for various experiments to be carried out to achieve the objectives.

The heat transfer coefficients calculated from the Experimental calculations were found to be 19.8418 W/m$^2$ $^\circ$ C and 20.5029 W/m$^2$ $^\circ$ C respectively. The trends in the temperatures, wind velocity and relative humidity were also compared, so as to find the reasons for deviations. Consecutively, a clear distillate was obtained on both the days, with favourable parameters. A CFD Simulation was carried out on the same, taking the observations from the experiments, location for solar radiation calculation and considering hexagonal meshing.

The productivity and heat transfer coefficient results from both Simulation and Experiments were thus compared, to check the errors and losses. The difference of 9% persists, due to various loses in the experimental set up. Whereas, the temperature trends of both simulation and Experiments had a similar behaviour, with an offset of $20^\circ$ C. The reasons for the difference are the assumptions made during the simulation and also that the solar radiations in simulation don’t take into account the natural offset; only consider the coordinate of the location.
10. Further Research

Future potential research could further test the suggested potential interventions to increase yield and efficiency of the simple Basin Solar Still, along with further proposing methodologies to enhance productivity of the simple Basin-type Solar Still. The design can be developed based on the optimum conditions obtained by Simulation results.

The following modifications and additions can be made in the still and the analysis to achieve the goals.

- Parameters such as solar intensity and absorptivity can be measured.
- Effects on productivity by increasing the absorptivity (by painting the base black).
- Addition of mirrors/ Reflectors - The productivity of the still can be enhanced using internal reflectors. The addition of mirrors will lead to multiple reflections inside the still so as to trap more heat, thus increasing the evaporation in a solar still.
- Nanoparticle - Another suggestion is the addition of a layer of discrete, imperforate inert solid nanoparticles. This particle should act as a black surface, to increase the absorptivity and further enhance evaporation.
- Effect of dropwise condensation on the heat transfer in the still.
- The basin of still can have a sandy heat reservoir and weirs to keep water shallow and improve the distribution of water on evaporation.

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