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# Theoretical and Simulation Prediction of Optimum Cover Inclination To Prevent Fall-Off Condensed Water Droplets

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**Abstract**

This study presented theoretical and simulation predictions to find the optimum glass cover inclination angle that can allow the water droplet underneath the surface to slide along it without fall-off. As a case study, the solar still main component that plays a big role on it is performance is the transparent glass cover that permits solar rays to pass through it and is used as a condensation surface for water vapor. The inclination angle of the cover is a very important parameter that provides confined space to increase the condensation process by fast cooling of the surface and result in more freshwater productivity. The theoretical prediction is obtained by modeling a set of mathematical equations that contain the main parameters necessary to slide the droplet along the surface without detaching it and solving them by using the MATLAB computer program. The simulation technique for the volume of fluid method uses the volume fraction equation with the level set applied in ANSYS Fluent software. The 3D model was created, and a water droplet was applied with adhesion force on the glass. It was found that the size of the droplet represented by its critical radius is a function of inclination angle. Also, it is found that for the angles larger than $15^{o}$, water droplets slide over the surface without separation. The optimum cover inclination provides both smooth slidings of droplet along with it and a suitable confined area that increases the rate of evaporation and condensation.

**Paper type**: Research paper

**Keywords**: Condensation at the inclined surface, inclination angle, solar still cover, droplet sliding, droplet fall-off.

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## Introduction

The water distillation process that obtained artificially from brackish water replicates the way nature makes rain, that is, the source of heat can evaporate the water. The vapor rises until it reaches a cold environment, then the condensed water droplets will perform. Solar thermal energy from the sun is considered a renewable source of heat that can be used for different applications, as stated by Alshqirate *et al*. (2015) and (2020). Solar trough collectors are modeled and analyzed for electric energy production potential by utilizing thermal energy obtained from the sun. Also, it can be used to obtain drinkable water from the sea and grey water using solar still. In a solar still, the sunlight passes through the transparent cover, the water inside evaporates, then the vapor condenses at the inner side of the cover because of temperature difference. Pure condensed, distilled water droplets will slide along the cover until it reaches the water collector. Sharma *et al*. (2016) presented a review of passive energy obtained at single slope solar still. Many parameters that affect the design of solar are still reviewed, i.e., the depth of water in the basin, type of metal used to construct the basin, the type of transparent cover, the inclination angle of the cover, the wind velocity, ambient temperature etc. Also, this review stated that the direction of the glass cover inclination of the solar still depends on the latitude of the location. Research papers and developments on solar still were reviewed by Kabeel and El-Agouz (2011). It is found that the efficiency of the solar still depends on many parameters as location, solar intensity, and basin water depth. Resolution of a mathematical model of a solar still carried out by Abdenacer and Nafila (2007). The results show that as the difference in temperature inside and outside the solar still increases, the efficiency of the system will be enhanced.

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Abu-hijleh and Mousa (1997) concluded that the efficiency of the solar still can be increased by using a water film to cool the glass cover of the solar still. The valuable information (productivity and efficiency of different solar stills), concerning the construction and design of solar stills to demineralisation of saline water, was determined by Elnesr and Soliman (1964). A double slope solar still unit that faces north and south directions for a lower latitude place was suggested by Kalidasa and Srithar (2011) with different wick materials, and by Manchanda and Kumar (2015). For a part of the year, the solar still covers facing the sun rays which are near to normal inclination on south for lower latitude regions, and for the rest of the year, the sun rays are close normal on the north and facing the other side of the still cover as explained by Dimri *et al*., (2007). The greenhouse effect can be obtained inside the solar still as the sun ray passes through the transparent glass cover. When the inclination of the cover is equal to the latitude angle of the site where the experiment conducts, it will receive normal solar incident. Alshqirate *et al*., (2020) improved experimentally the pyramid solar still that used for water desalination. The pyramid glass cover was designed and mounted at an angle equal to the latitude of the location where the experiment was carried out. Also, as the water droplets condensed at the inner surface of the glass cover, it slides down the cover to the accumulation channel at the bottom. The inclination of the cover will help in collecting the droplets, but if the inclination is less, the condensate droplets may detach the glass cover before it reaches the collecting tray and falls back to the basin. Many studies reported their results regarding the degree of inclination provided to the covers of solar stills, i.e., Tiwari *et al*., (2007), and Somwanshi *et al*., (2013). Based on the previous literature reviews, it is found that the condensing cover slope of solar still directly affects its productivity. The best choice of the inclination angle of the cover will achieve many advantages as maximising water productivity by allowing condensed water droplets to run smoothly to the collecting tray without reflecting the basin, fast flow of droplets maximising solar radiation amount that passes through the glass to the water surface at the basin which is, in turn, enhanced the absorption of solar radiation and also helps to insulate the exterior surface of the cover to reduce heat losses. In this study, theoretical and computer simulation techniques were used to predict the optimum inclination of the glass cover used in the solar still to achieve two things: get the maximum amount of required solar thermal energy necessary to evaporate water and to ensure that no condensed water droplets detach the inner surface of the cover when sliding down to the collecting tray.

# 1 Materials and Methods

## 1.1 Theoretical Analysis

Xie *et al*., (2018) presents different modes of droplet detachment over inclined surfaces in **Figure 1**. For the solar still system, the dripping mode was presented for condensation of evaporated water at the inner side of the inclined cover glass plate. The condensed water slides down the glass cover, accumulated and collected. Distilled water productivity depends on the accumulated amount, which is theoretically must equal the amount of condensed water. Water droplet slides under the action of both surface tension and shear forces. The surface tension force completed by the action of gravity force. By balancing forces perpendicular to the tilted surface, as stated by Sikarwar *et al*., (2011), the critical dripping drop size can be obtained. To avoid dripping phenomena, the dripping droplet size can be prevented by choosing an optimum inclination angle ($\theta$) of the tilted surface as depicted by Sivakumaran and Jidhesh (2016) in **Figure 2**.

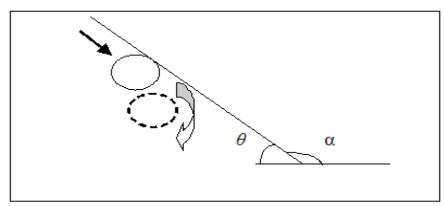


**Fig. 1** Droplet detachment modes presented as sliding mode (a), rolling mode (b), lifting mode (c) and dripping mode (d).

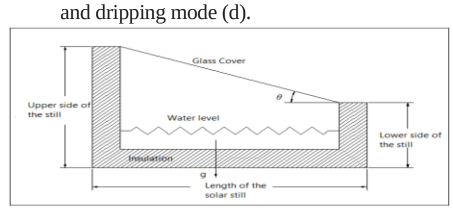


**Fig. 2** Inclination angle (θ) of the tilted glass cover of solar still.

The scarcity of mathematical models that can be used to describe this phenomenon is because of the following reasons:

1- The droplet may grow without sliding, then dripping can occur and Bond number (*Bo*) represents the relationship between the surface tension force and buoyancy force.
2- The nature of the surface (hydrophobic or hydrophilic surfaces).
3- The droplet may slide with and without dripping and Webber number (*We*) characterising the relation between the inertia force and surface tension forces.

Xie *et al*., (2018) presented a set of equations that contain many parameters:

1- Non-dimensional *We*, *Bo*, and Reynold (**Re**) numbers.
2- Inclination angle parameter ($\theta$).
3- Wettability parameters and contact angle hysteresis.

## 1.2 Mathematical model formulation and solution

Sikarwar *et al*., (2011) and Battoo *et al*., (2010) presented an equation of the droplet contact angle variation along the inclined surface. The droplet will be deformed when sliding along the inclined surface and caused a contact angle hysteresis as shown in **Figure 3**. The contact angle is assumed to vary linearly from receding to advancing angle, as follows:

$$\alpha = \alpha_{adv} + \frac{\pi - \alpha_{rcd} - \alpha_{adv}}{\pi}\varphi \tag{1}$$

Where the contact angle is α, the advancing angle is $\alpha_{a\,dv}$ , the receding angle is $\alpha_{rcd}$ and the azimuthal angle is $\varphi$.

Two forces are exerted on the droplet besides the gravity force as depicted in Fig. 3. The force parallel to the inclined surface is the retention force ($F_r$) which can be expressed as a function of surface tension as follows:

$$F_r = 2\int_0^{\pi} \sigma .\, r_b . \cos\alpha \;. \cos\varphi \;. d\varphi \tag{2}$$

Where the surface tension is $\sigma$ and the base radius of the droplet is $r_b$.

The force perpendicular to the inclined surface is the surface tension force ($F_s$) and can be expressed as follows:

$$F_s = 2\int_0^{\pi} \sigma \,.\, r_b . \sin\alpha \;. d\varphi \tag{3}$$

The two components of the gravity force ($F_g$), parallel and perpendicular components, can be obtained as follows:

$$F_{g(parallel)} = \frac{\pi\, r_b^3 (\,2 - 3\cos\alpha_{avg} + cos^3\alpha_{avg})}{3\, sin^{\,3}\alpha_{avg}}\, \rho\, g \sin\theta \tag{4}$$

$$F_{g\,(perpendicular)} = \frac{\pi\, r_b^3 (\,2 - 3\cos\alpha_{avg} + cos^3\alpha_{avg})}{3\, sin^{\,3}\alpha_{avg}}\, \rho\, g \cos\theta \tag{5}$$

Where the fluid density is , the gravity acceleration is $g$, and the average of the contact angles $\alpha_{avg}$is expressed as:

$$\alpha_{avg} = \frac{\alpha_{rcd} + \alpha_{adv}}{2} \tag{6}$$

By assuming the inclined surface as a hydrophilic surface, the droplet can be taken as a part of a sphere with an average contact angle $\alpha_{avg}$.

It is very necessary to obtain the dimensions of the droplets to maintain their balance, free and fast movement along the inclined surface without fall-off.

By balancing forces parallel to the inclined surface, the critical radius ($r_{crit}$) of the droplet that allows it to slide can be obtained as follows:

$$r_{crit}^2 = \left[\frac{3\,\sigma \sin\alpha_{avg}}{\pi\,(2 - 3\cos\alpha_{avg} + cos^3\alpha_{avg})\rho\, g\, sin\,\theta}\right] * [\frac{\pi}{2\pi - \alpha_{rcd} - \alpha_{adv}}\{sin(2\pi - \alpha_{rcd}) - sin\alpha_{adv}\} + \frac{\pi}{\alpha_{rcd} + \alpha_{adv}}\{sin(\alpha_{rcd}) + sin(\,\alpha_{adv})\}] \tag{7}$$

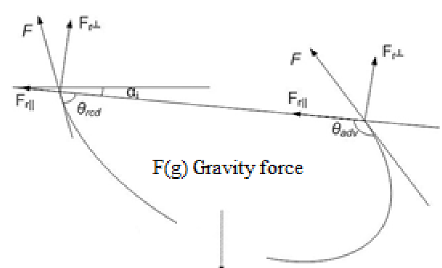


**Fig. 3** Deformed water droplet on the inclined surface.

While the maximum radius of the droplet ($r_{max}$) that achieves its stability on the inclined surface can be obtained by balancing perpendicular forces as follows:

$$r_{max}^2 = \left[\frac{6\,\sigma * \sin\alpha_{avg} * (cos(\alpha_{rcd}) + cos(\,\alpha_{adv}))}{\rho\, g\, cos\,\theta * (2 - 3\cos\alpha_{avg} + cos^3\alpha_{avg}) * (\,\pi - \alpha_{rcd} - \alpha_{adv})}\right] \tag{8}$$

And the volume of the approximated spherical shape of the droplet ($V$) can be expressed as follows:

$$V = \frac{\pi\, r_b^3 (\,2 - 3\cos\alpha_{avg} + cos^3\alpha_{avg})}{3\, sin^{\,3}\alpha_{avg}} \tag{9}$$

After the droplet is formed and reached a critical volume, it is sliding and speed up along the inclined surface. Sakari *et al*. (2007) assumed a linear distribution of the droplet velocity. The shear stress and velocity gradient are introduced as follows:

$$\frac{du}{dy} = \frac{U}{h} \tag{10}$$

$$\tau = \mu \frac{du}{dy} \tag{11}$$

By balancing the forces on the droplet through its movement along the surface, the acceleration can be calculated as:

$$\sum forces = ma = F_{g\,(parallel)} - F_v - F_r \tag{12}$$

Where the shear force is $F_v$.

And the velocity of the droplet from onetime interval to another one can be calculated as:

$$U_t = U_{t-1} + a\,.dt \tag{13}$$

A MATLAB program was used to solve the set of equations and to calculate different parameters by trial-and-error technique under-considered conditions and assumptions:

- The inclined surface is assumed as a hydrophilic surface
- The droplet shape is taken as a part of the sphere
- The droplet dimensions between $r_{crit}$ and $r_{max}$
- The droplet volume not to exceed the critical volume
- Inclination angle of the surface $10° \leq \theta \leq 50°$
- Different saturation temperatures
- Inclined surface with length 400 mm assumed as a case study

The main finding of this solution is to obtain the optimum inclination of the surface that allows the droplet to travel along with it before fall-off.

### 1.3 Numerical Analysis

Simulation technique will be used to study this phenomenon, simplify, and predict the appropriate inclination angle of the proposed cover to collect the largest amount of condensed water vapor without fall-off back to the basin.

Numerical modelling of two-phase flow was used to model the motion of the water droplet along the down surface of a glass inclined plan. The volume of fluid (VOF) model uses the volume fraction equation to solve the two-phase air bubble interface. This can be achieved by solving the continuity equation for the one-phase volume fraction.

In general, Yeoh and Tu (2009) introduced the volume fraction of phase $q$ by using the method of mass conservation as follows:

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\gamma_q\rho_q\right) + \nabla\cdot\left(\gamma_q\rho_q\,\vec{u}_q\right) = S_q + \left(\dot{m}_{qp} - \dot{m}_{pq}\right)\right] \tag{14}$$

Where; $\gamma_q$ is the volume fraction of phase $q$, it has three values:

$\gamma_q$=1, proposed cell full of phase q.

$\gamma_q$=0, proposed cell empty of the phase q.

0<$\gamma_q$<1, the proposed cell of the interface of both phases.

$\vec{u}_q$ is the phase q vector of velocity.

$S_q$ is phase q void fraction source term.

$\dot{m}_{qp}$ is the mass transfer from phase q to phase p.

In this study, the primary phase is assumed to be liquid. Based on this assumption, the above equation applies.

The following equation presented the other phase volume fraction:

$$\gamma_q + \gamma_p = 1 \tag{15}$$

It is noticed that discontinuity of the function appeared through the two-phase interface in the cell.

The other function, which is called a level-set function $\emptyset$ (*x*,*t*) can be used to track the two-phase interface.

The continuous and smooth level-set function defined by Olsson *et al*., (2007) can predict accurately the two-phase interface curvature and the surface tension force resulting from this function as follows:

$$\emptyset(x,t) = \begin{cases} +|d| & \text{if } x \in \text{the primary phase} \\ 0 & \text{if } x \in \text{the interface} \\ -|d| & \text{if } x \in \text{the secondary phase} \end{cases} \tag{16}$$

The momentum equation which is presented by Yeoh and Tu (2009) for a single-phase can be applied and solved in this study as follows:

$$\frac{\partial}{\partial t}(\rho\vec{u}) + \nabla\cdot(\rho\vec{u}\vec{u}) = -\nabla P + \nabla\cdot\vec{\tau} + \rho\vec{g} \tag{17}$$

Where the density of the fluid is $\rho$, the tensor of shear stress is $\vec{\tau}$, the dynamic viscosity is $\mu$, the pressure P, the fluid velocity vector $\vec{u}$ and the gravitational acceleration is defined as a vector is $\vec{g}$. The model used for simulating the sliding drop is shown in **Figure 4**.

### 1.4 Simulation Prediction

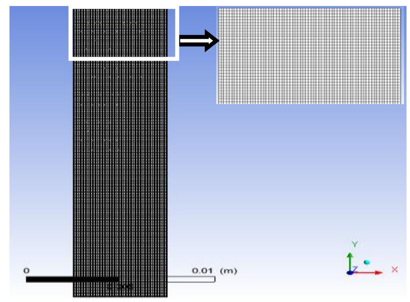


**Fig. 4** The model used for the simulation.

The mesh was created using Ansys ICEM for making a 3D model of 947439 tetrahedron elements of a uniform structured grid. The domain dimensions were 5x5x25 mm. The starting droplet shape was considered as a part of a sphere with a base diameter of 4.5mm. the contact angle between the droplet and the glass plan was considered as 50ºC. The domain is illustrated in **Figure 5**. The considered boundary conditions are the wall for the surface on which the droplet slides and the opening for the other surfaces.

## 2 Results and Discussion

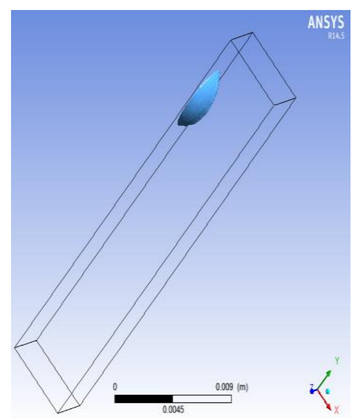


**Fig. 5** Computational domain with the initial droplet shape.

The critical radius of the droplet at which it slides on the inclined surface is a function of the inclination angle and the contact angle. As the inclination of the surface increases, numerous small drops are performed, which in turn prevents the fall-off of condensed droplets and increase the heat transfer coefficient, that is, increasing of cooling rate of the surface. This result is compatible with what Battoo *et al*., (2010) have obtained.

By solving the set of equations numerically, it is found that the droplet reaches the end of the inclined surface at inclination angles of more than $15^o$, as presented in **Table 1**.

By increasing the inclination angle of the cover by more than $50^o$, the area confined between the glass cover and the top surface of the water inside the basin increases, which in turn decreases the rate of evaporation because of the decrease of confined temperature.

In the simulation technique, different inclination angles were tested. In all the simulations, a starting droplet position is started, and a transient simulation is performed to notice the nature of the droplet sliding on the inclined surface for each inclination angle. For the first inclination angle of 10º, the advancement of the droplet motion is shown in **Figure 6**. It can be noticed that at a $10^o$, inclination angle, the droplets slide and starts to separate from the surface very fast, as shown from the time shots of the droplet shape. The last shape occurs at 11mm from the top end of the plan. Battoo *et al*., (2010) stated the mechanism of drops fall-off and sliding off condensed water at $10^o$ inclined surface. For the next angle of $15^o$, the variation of the droplet shape with time is shown in **Figure 7**. It can be observed as well for the inclination angle of $15^o$ that after a small time, the droplet separates from the surface. The last shape occurs at 12.8mm from the top end of the plan. At these two angles of $10^o$ and $15^o$, inclinations, the separation of the droplet from the glass surface takes place at a short time. Sikarwar *et al*., (2011) recorded experimentally and by simulation sliding, sweeping, and fall-off of condensed droplet condensation at the inclined surface of $15^o$. **Figure 8** represents the shape of the deformed droplet at the inclination angle of $20^o$. The droplet slides over the surface without separation and reaches the end of the surface of 25 mm.

**Table 1** The distance travelled by the droplet along 400 mm inclined surface before fall-off.

| Inclination angle ($\theta°$) | Distance (mm) |
|---|---|
| 10 | 177.4 |
| 11 | 210.9 |
| 12 | 257.7 |
| 13 | 294.7 |
| 14 | 333.0 |
| 15 | 372.5 |
| 16 | 393.2 |
| 17 | 400 |
| 18 | 400 |
| 19 | 400 |
| 20 | 400 |
| 50 | 400 |

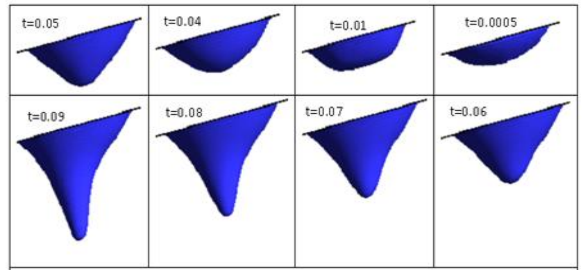


**Fig. 6** The formation shape of the droplet at 10º angle of inclination.

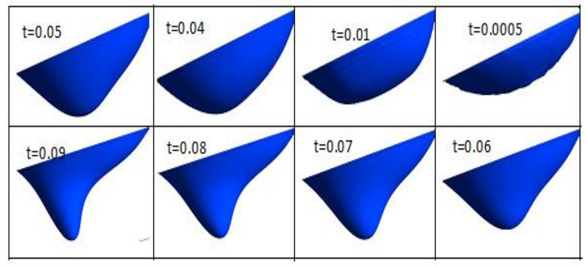


**Fig. 7** The formation shape of the droplet at 15º angle of inclination.

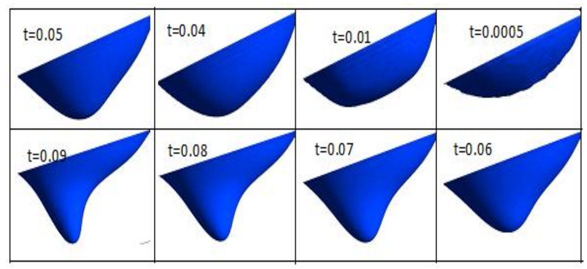


**Fig. 8** The formation shape of the droplet at 20º angle of inclination**.**

## Conclusions

In the present study, a mathematical model and three-dimensional simulation were performed for the water droplet sliding over an inclined plane of the glass cover. It is concluded that at small angles of inclination for the glass cover, the condensed water droplets at the cover inner surface start to separate and fall off. While for the angles higher than 15$^o$, the droplets slide along the inclined surface without separation.

## Nomenclature

| | | |
|---|---|---|
| $Bo$ | =Bond number | [-] |
| $F_{g(parallel)}$ | =Parallel component of the gravity force | [N] |
| $F_{g\ (perpendicular)}$ | =Perpendicular component of the gravity force | [N] |
| $F_r$ | =The retention force | [N] |
| $F_s$ | =The surface tension force | [N] |
| $F_v$ | =The shear force | [N] |
| $P$ | =Pressure | [N/m$^2$] |
| $r_b$ | =The base radius of the droplet | [m] |
| $r_{crit}$ | =The critical radius of the droplet | [m] |
| $Re$ | =Reynold number | [-] |
| $r_{\max}$ | =The maximum radius of the droplet | [m] |
| $S$ | =Source term of the void fraction | [-] |
| $u$ | =Velocity | [m/s] |
| $V$ | =The volume of the droplet | [m$^3$] |
| $VOF$ | =Volume of fluid | [-] |
| $\theta$ | =Inclination angle | [-] |
| $\gamma$ | =Volume of fraction | [-] |
| $\dot{m}_{qp}$ | =The mass transfer from phase q to phase p [kg/s] | [-] |
| $\vec{u}$ | =Velocity vector | [-] |
| $\emptyset$ | =Level-set function | [-] |
| $\rho$ | =Fluid density | [kg/m$^3$] |
| $\vec{\tau}$ | =Shear stress tensor | [-] |
| $\mu$ | =Dynamic viscosity | [Pa. s] |
| $\vec{g}$ | =Gravitational acceleration vector | [-] |
| $\alpha$ | =The contact angle | [rad] |
| $\alpha_{a\,dv}$ | =The advancing angle | [rad] |
| $\alpha_{rcd}$ | =The receding angle | [rad] |
| $\varphi$ | =The azimuthal angle | [rad] |

| | | |
|---|---|---|
| $\sigma$ | =The surface tension | [N/m] |
| $\alpha_{avg}$ | =The average of the contact angle | [-] |
| $We$ | =Webber number | [-] |

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