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Research paper

Impact of Sky Conditions on The Performance of The Solar Still

Traore Damus Abdoul Aziz [1] *, Dianda Boureima [2], Combari Pagou Hartwig [1], Bamogo Kombassé [1], Ouedraogo Maneg-Sanga Pélagie Rosina [1]

[1] Renewable Thermal Energy Laboratory, University Joseph KI-ZERBO, Ouagadougou, Burkina Faso
[2] Research Institute of Applied Sciences and Technologies, National Center for Scientific and Technological Research, Ouagadougou, Burkina Faso
**Corresponding author E-mail: traoredamus35@gmail.com*

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Abstract

As part of improving the performance of active stills, we numerically studied the effects of sunlight on a concentrating still. This is a double-slope solar still under which a parabolic trough concentrator was placed. We were particularly interested in the impact of sky conditions on productivity, overall and internal efficiency, and exergy efficiency. Applying the energy balance method to the different components of the still allowed us to calculate the productivity and the various efficiencies of the system. Our system was simulated for the climatic conditions of the city of Ouagadougou (located at 12.35 North latitude and 1.32 West) and for April. These results show that the nature of the sky has a significant impact on the operating characteristics of the still. Indeed, the productivity, the overall, internal, and exergy efficiency of the distiller are a function of the sunshine and therefore depend on the nature of the sky. These characteristics improve with the increase in sunshine. The best operating characteristics are obtained for a clear sky because the sunshine is higher. We have a maximum overall radiation of 936.504 W/m² for a clear sky against 866.24 W/m² and 755.69 W/m² for a sky with normal atmospheric conditions and a polluted sky. For a clear sky, we obtained a maximum productivity of 0.0014 kg/'s against 0.0011 kg/s and 0.0007 kg/s for a sky with normal atmospheric conditions and for a polluted sky. It was concluded that productivity, the different efficiencies are strongly affected by sunshine. The higher the radiation intensity, the better the productivity of the distiller.

Keywords: *Distiller; Concentration; Sunshine; Sky Conditions; Performance.*

1. Introduction

The demand for fresh water continues to increase due to population growth, droughts, and its use in several areas such as agriculture, industry, health, etc. Indeed, during recent decades, most regions of the world have received insufficient rainfall, which leads to an increase in water salinity and a water shortage. The world population increased by 4.3 billion between 1900 and 2000, rising to 8 billion in 2025, which has led to a decrease in the average quantity of drinking water available per capita per year (from 6,600 to 4,800 m³, a reduction of almost a third). It is therefore essential to reduce the gap between demand and supply of fresh water by developing alternative water purification technologies. Among these technologies, desalination is one of the oldest technologies used by humans for water purification. Conventional industrial desalination technologies are divided into two main categories: thermal and membrane phase change processes. Thermal processes are those that use heat to vaporize water, which will then be condensed into drinking water. These techniques are vacuum desalination, freeze desalination, and distillation processes. Membrane processes are reverse osmosis and electrodialysis. These processes use semi-permeable membranes for the purification of seawater and brackish water. These technologies require a Chemical pretreatment of brackish water and chemical posttreatment [1]. In addition, these technologies are very energy-intensive and expensive. Solar distillation is therefore a more promising, simple, and economical technique for the purification of salt water and brackish water. This technique uses solar energy as an energy source. Solar stills are divided into two categories: passive and active systems. In active solar stills, additional thermal energy can be supplied to the passive solar still by using an external source to increase the evaporation rate. On the other hand, passive systems do not use any external energy source [2]. Single or double-slope solar stills are the most designed and studied because of their simplicity to realize. Unfortunately, their performances are not high enough. To improve their performances, they can be coupled to a concentrator, generally a parabolic cylinder, to flat collectors, to vacuum tubes ... The addition of certain phase change materials, such as paraffin in brackish water, and the use of certain materials in the construction of the device also improve the performance of the stills. Works in the literature include those of Hussein Amiri and al [3] designed and experimentally studied a new autonomous desalination system, composed of a parabolic cylinder collector placed under a double slope solar still. Dubey et al. [4] coupled evacuated tubes with a double slope solar still operated by a pump. Rajamanickam et al [5] added storage materials in their device; they noted the improvement of the operating parameters. Vignesovacan et and [6] carried out experimental work using different absorbent materials for the construction of the basin of a solar still. They found that materials with low thermal conductivity offer higher efficiency than galvanized materials. However, whatever the performance of a solar still, certain meteorological factors such as solar radiation hitting the ground, ambient temperature, wind velocity, and humidity greatly influence the performance of a solar still [7]. Sory Diarra and al [8] carried out an experimental study of the climatic effects on a mobile wick still with an external capacitor. Omar and al [9] showed in their experimental study that the productivity of a solar still is directly related to the concentration of solar radiation. Sebali and al [10] conducted an experimental study of the effect of wind speed and the effect of sunlight on passive and active solar distillers. Ghoneye and al analyzed a solar still and established empirical equations to show the dependence of a still's productivity on ambient temperature [11]. The results show that the productivity of stills is directly related to ambient temperature. Dinesh Mevada and al. [12], during a study on a solar still coupled with evacuated tubes, a condenser, and fins, found that different parameters such as ambient temperature, solar radiation, and wind speed have a variable effect on distillate production. Our work consists of studying the influence of the nature of the sky on the performance of an active solar still. This is a double slope solar still under which a parabolic trough solar concentrator has been placed. Many researchers have also studied the impact of the nature of the sky on the performance of a still. A.Deliou and al [13] showed the influence of the nature of the sky on the overall efficiency of a double slope solar still. Mandi Benaissa et al [14] studied the influence of the nature of the sky on the productivity of a single slope still and a hybrid still. They concluded that the productivity of both stills is higher under a clear sky. Almuhanna et al [15] showed that the productivity of a single-slope solar still is dictated by the sunlight. Nafey and al [16] studied various parameters that can affect the performance of a still; they concluded that solar radiation is one of the parameters that greatly affects the performance of a solar still. Rahmani and al [17] studied the effect of a condenser on a solar still in all seasons and found that the performance of the device varies from one season to another. Mokhtar N Quam et al [18] studied the influence of meteorological parameters on a distiller coupled with a parabolic concentrator; they concluded that an increase in solar radiation leads to an increase in freshwater yield and system efficiency. In this work, we will focus on the impact of the nature of the sky on the operating characteristics of our distiller, namely productivity, overall efficiency, internal efficiency, energy efficiency, and the performance factor.

2. Materials and methods

2.1. Description of the device

The solar still studied is a high-temperature active solar still. It consists of a double-slope solar still under which a parabolic trough concentrator is placed. The still consists of a double-slope glazing and a tank containing the water to be distilled. The glazing consists of two identical panes measuring 1.3m x 0.03m and 4mm thick. The glazing is inclined at an angle of 20 degrees relative to the horizontal. The tank containing the water to be distilled is made of stainless steel, measuring 1.3m x 0.06m x 0.005m. The bottom of the tank has a thickness of 0.001m. The latter is painted black. Gutters are installed at the tank level to collect the distillate. The purpose of the concentrator is to focus the reflected rays at the level of the tank, which makes it possible to increase the temperature of the water contained in the tank. With this type of distiller, the temperature of the water contained in the tank of the distiller is higher than 100°C, which increases the productivity and efficiency of the device. The linear axis solar concentration system improves the performance of conventional distillers. A numerical study of the device was carried out by Traoré and al. During their study, they obtained satisfactory results. The maximum temperature of the absorber was 112°C, and the maximum productivity was 3.96 kg/m²h, which is significantly higher than the productivity of conventional distillers and even some active distillers [19]. A. Dellou and al [13] with a passive double slope distiller obtained a maximum hourly productivity of 0.55 kg/m²h. R. Menina and al [20] obtained a maximum productivity of 0.45 kg/m²h with a distiller coupled to a flat collector.

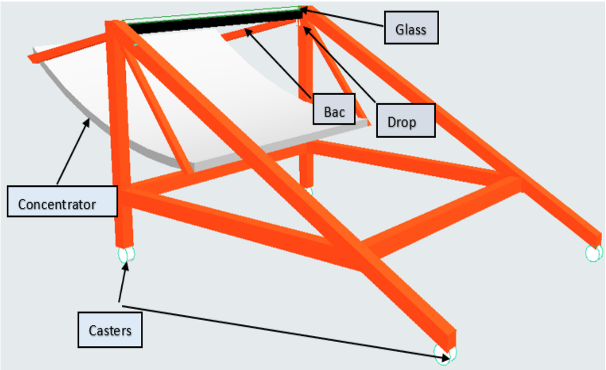


Fig. 1: Schema Diagram of the Device.

2.2. Heat balance at the level of the different elements of the device

We established simplifying assumptions, established the heat balances at the levels of the different elements of the device, and solved these equations using the Runge Kutta method of order 4.
Assumptions:

- The heat transfer is unidirectional
- The temperature of each component is uniform
- The physical properties of the materials are constant

Figure 2 shows the different transfers that take place in the distiller.

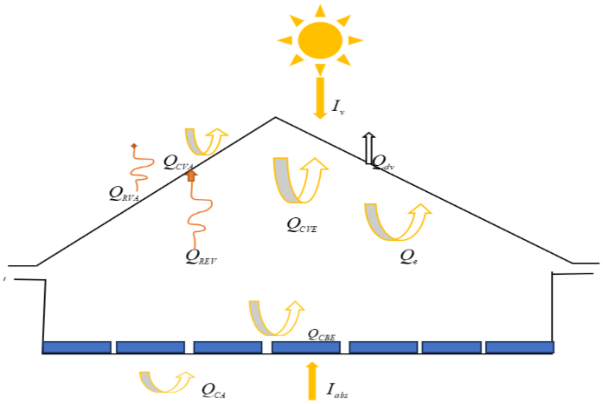


Fig. 2: The Different Transfers in the Distiller.

- Heat balance at the outer window :

$$\frac{M_V C_{pv}}{2A_V}\frac{dT_{vex}}{dt} + h_{RVA}\left(T_{vex} - T_c\right) + h_{CVA}\left(T_{vex} - T_c\right) - \frac{\lambda_V}{e_V}\left(T_{vin} - T_{vex}\right) - I_V = 0 \quad (1)$$

Where h_{CVA} is the convection transfer coefficient between the window and the ambient environment (W/m²). It is determined by using the relationship [21]:

$$h_{CVA} = 5,7 + 3,8V \quad (2)$$

With h_{RVA} is the radiation transfer coefficient between the window and the ambient environment.

This coefficient is determined by the equation (3) [22]:

$$h_{RVA} = \varepsilon_v \sigma\left[(T_{vex}^{\ 2} + T_c^{\ 2})(T_{vex} + T_c)\right] \quad (3)$$

T_c is the sky temperature. It is determined by the empirical relationship [23] :

$$T_c = 0.0552 T_a^{1.5} \quad (4)$$

$$h_{cv} = \frac{\lambda_v}{e_v} \quad (5)$$

h_{cv} being the conduction transfer coefficient through the window.

$$I_v = \alpha_V I_G \quad (6)$$

I_v is the solar power absorbed by the window.
I_G Global radiation intensity

$$I_G = I_D + I_d \quad (7)$$

I_D is the direct solar radiation for a given surface. It is expressed as:

$$I_D = I_o C.A.\exp(-\frac{B}{\sinh} x \frac{P}{1000}) x \cos i \quad (8)$$

I_o is the solar constant, its value is 1350W/m²
C is the correction factor due to the variation in the distance from the Earth to the Sun
A and B are coefficients reflecting atmospheric disturbances (see table)
P is the atmospheric pressure, which depends on altitude
I_d is the diffuse radiation

$$I_d = \varphi_1 + \varphi_2 \quad (9)$$

φ_1 is the diffuse flux emitted by the celestial vault.
φ_2 is the flux emitted by the ground.

- Heat balance at the level of the interior window :

$$\frac{M_v C_{pv}}{2A_V}\frac{dT_{vin}}{dt}+\frac{\lambda_v}{e_v}\left(T_{vin}-T_{vex}\right)-h_{REV}\left(T_E-T_V\right)-h_{CVE}\left(T_E-T_{vin}\right)-h_{EV}\left(T_E-T_{Vin}\right)-I_v=0 \tag{10}$$

Using the Dunkle model [24] and taking into account the inclination of the glazing of our device, we have

$$h_{CVE}=0,884[(T_E-T_v+\frac{(P_E-P_V)(T_E+273,15)}{298,910^3-P_E})(\frac{1+\cos\beta}{2})]^{(1/3)} \tag{11}$$

h_{CVE} is the convection transfer coefficient.

h_{REV} : The radiation transfer coefficient between the glass and the water. This coefficient is determined using relation [25] :

$$h_{REV}=\varepsilon_{eff}\sigma\left[(T_E{}^2+T_{vin}{}^2)(T_E+T_{vin})\right] \tag{12}$$

h_{EV} the evaporation transfer coefficient is determined by relation [26]:

$$h_{EV}=16,273.10^{-3}h_{CVE}\left(\frac{P_E-P_v}{T_E-T_v}\right) \tag{13}$$

$$P=exp\ (25,317-\frac{5144}{T+273}) \tag{14}$$

P is the partial vapor pressure. There are several relationships for determining the partial vapor pressure, but in our study, we used the Fernandez and Chargoy relationship [27], which is the simplest and most widely used.

- Heat balance at the absorber

$$\frac{M_{abs}C_{pabs}}{A_{abs}}\frac{dT_{abs}}{dt}+h_{abs}\left(T_{abs}-T_E\right)+h_{CVA}\left(T_{abs}-T_a\right)-I_{abs}=0 \tag{15}$$

With:

$$h_{abs}=\frac{N_u\lambda_f}{L} \tag{16}$$

h_{abs} is the convection transfer coefficient between the absorber and the water.

The Nusselt number is determined based on the Grashof number G and Prandit number P

If $G_r\leq 10^5$ then $N_u=1$ (17)

If $10^5<G_r<210^7$ then $N_u=0.54\left(G_r P_r\right)^{0.25}$ (18)

If $G_r>210^7$ then $N_u=0.14\left(G_r P_r\right)^{0.33}$ (19)

I_{abs} is the solar power absorbed by the absorber

$$I_{abs}=\alpha_{abs}\rho C_g I_D \tag{20}$$

I_D : The direct radiation

α_{abs} : The absorption coefficient of the absorber

ρ: The reflectivity coefficient of the parabola

- Heat balance at the water :

$$\frac{M_E Cp_E}{A_E}\frac{dT_E}{dt}+h_{REV}\left(T_E-T_V\right)+h_{CVE}\left(T_E-T_{vin}\right)+h_{EV}\left(T_E-T_{Vin}\right)-h_{abs}\left(T_{abs}-T_E\right)-I_E=0 \tag{21}$$

$$I_E=\alpha_E(\tau_v I_v+\tau_{abs}I_{abs}) \tag{22}$$

I_E is the solar power absorbed by the water.

2.3. Performance elements

- Productivity

The productivity of a distiller or the flow rate of distilled water is defined as its efficiency. It is the quantity of water produced per unit area per day. It is determined by the following relationship [28]:

$$md = \frac{Q_{ev}}{L_V} \tag{23}$$

Where Q_{ev} and L_V are respectively the heat flux transferred by evaporation and the latent heat of vaporization of the water.

- Overall Efficiency

It shows the performance of the distiller about the energy absorbed by the distiller. The overall efficiency of an active distiller is determined by the relationship [29]

$$n_g = \frac{Q_{ev}}{\rho C_g I_D A_{abs} + I A_v} \tag{24}$$

Q_{ev} , I_D , I , A_{abs} and A_v are respectively the quantity of heat used for evaporation, direct solar radiation, global solar radiation, the surface area of the absorber, and the surface area of the glass

- Internal efficiency

This second efficiency shows the performance of the distiller in relation to the energy absorbed by the water. It is the ratio of the amount of heat used for evaporation to the amount of heat absorbed by the water [30]. This efficiency is expressed as :

$$n_{in} = \frac{Q_{ev}}{A_E I_E} \tag{25}$$

Q_{ev} , I_E and A_E are respectively the amount of heat used for evaporation, the solar energy absorbed by the water, and the water surface.

- The exergy efficiency,

Analyzing solar distillation systems using the energy concept may be insufficient to better understand the energy used in these mechanisms. The introduction of a new concept, 'exergy', will allow us to examine such a thermodynamic system to identify potential improvements. It is a qualitative value of the energy and the maximum work potential that can be obtained from the energy, depending on the ambient conditions. Exergy efficiency is defined as the ratio of the output exergy to the input exergy. In the case of our device, the output exergy is the evaporation exergy, and the input exergy is the solar exergy. The expression for exergy efficiency is given by the following equation:

$$n_{exer} = \frac{Exer\_ev}{Exer\_sun} \tag{26}$$

$Exer\_sun$ is the solar exergy flux falling on the solar still.

$Exer\_ev$ is the exergy evaporation flux.

- Still performance

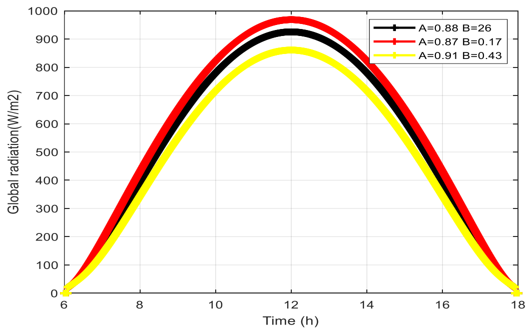
In order to characterize the operation of our solar still, we defined an instantaneous performance factor. Its expression is :

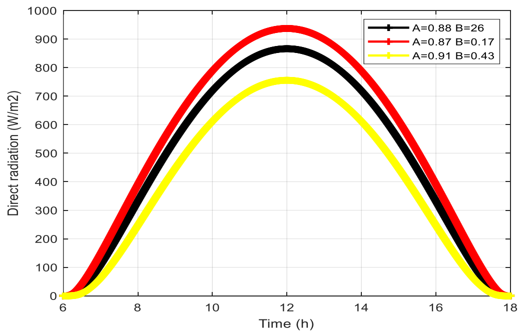
$$FP = \frac{md}{C_g I_D + I_V} \tag{27}$$

3. Results and discussions

3.1. Evolution of radiation

The following figures represent the evolution of global, direct, and diffuse radiation according to the nature of the sky.





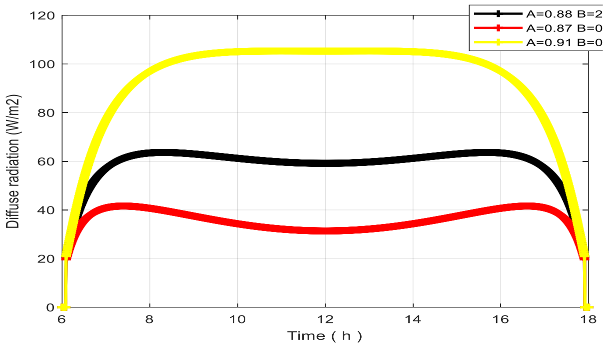


Fig. 3: Evolution of the Different Components of Solar Radiation.

These radiations increase gradually to reach their maximum values at noon and then decrease from the afternoon to reach a minimum value of 0 W/m² around 6 p.m. The maximum values of direct radiation for a clear sky, a sky with normal atmospheric conditions, and a polluted sky are respectively 936.504 W/m², 866.24 W/m², and 755.69 W/m².

The highest value is obtained for a clear sky. Diffuse radiation has a small evolution compared to direct radiation. The maximum values of diffuse radiation for a clear sky (A=0.88, B=0.26), a sky with normal atmospheric conditions (A=0.87, B=0.17), and a polluted sky (A=0.91, B=0.43) are respectively 59.14 W/m², 31.37 W/m², and 105.27 W/m². The highest value is obtained for a polluted sky. This is due to the nature of the sky. The maximum values of global radiation for a sky with normal atmospheric conditions, a clear sky, and a polluted sky are respectively 925.246 W/m², 968.409 W/m², and 860.86 W/m². The highest value is obtained for a clear sky. The most significant radiation, namely global and direct radiation, is that of a clear sky (A=0.87, B=0.17). This result is explained by the clarity of the sky. A large part of the solar radiation reaches the ground for a clear sky; this part becomes less important for a sky with normal atmospheric conditions and weak in the case where the atmosphere is polluted (industrial zone). Several authors, including Halloufi Quadi et al [19], have also reached the same conclusions for the three types of sky conditions.

3.2. Impact of the nature of the sky on productivity

Figure 4 shows the productivity of the distiller for normal atmospheric conditions for a clear sky and for a polluted sky.

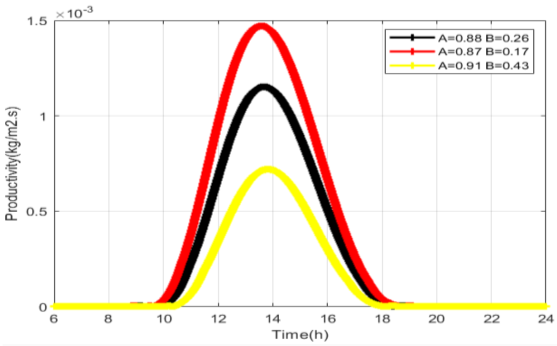


Fig. 4: Evolution of Productivity.

The first drops are collected from 10 a.m. The distiller's productivity begins to increase from noon to reach its maximum value around 3:46 p.m., then a decrease is observed to reach its minimum value from 6 p.m The maximum values obtained are respectively 0.0014 kg/m³s 0.0011 kg/m²s and 0.00071 kg/m²s for a clear sky (A-0.87, B-0.17), for a sky under normal atmospheric conditions (A-0.88, B-0.26) and for a polluted sky (A-0.91, B-0.43). The largest quantity of water collected is obtained for a clear sky. This is explained by the fact that the direct solar radiation reaching the device is very high under this sky condition, and consequently, the heat fluxes transmitted to the water by the glass and by the absorber are very high; hence, a high temperature difference between the brine and the glass, which will lead to high productivity. Researchers such as Al-hinai et al. and Mandi Benaissa et al. have reached the same conclusion: that the productivity of a solar still is greater for a clear sky than for normal atmospheric conditions and a polluted sky.

3.3. Impact of the nature of the sky on the performance factor

Figure 5 shows the impact of the nature of the sky on the performance factor of our device.

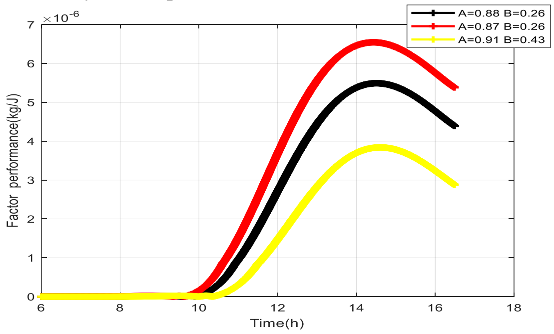


Fig. 5: Performance Factor Evolution.

The performance factor has a similar pattern to that of productivity. It begins its evolution at 10 a.m., then increases to reach its maximum value around 3 p.m., then begins to decrease rapidly. The maximum values obtained are respectively 6.54 10^{-6}kg/J, 5.4910^{-6} kg/J et 3.83. 10^{-6} kg/J under a clear sky (A=0.87, B=0.17), for a sky with normal atmospheric conditions (A=0.88, B=0.26), and a polluted sky (A=0.91, B=0.43). We note that the highest performance is obtained for a clear sky. This is quite normal because the performance factor is a function of the distiller's productivity. The previous figure shows that productivity is higher for a clear sky; hence, the performance factor is higher under this sky condition.

3.4. Impact of the nature of the sky on overall efficiency

Figure 6 shows the evolution of efficiency for normal atmospheric conditions, for a clear sky, and a polluted sky.

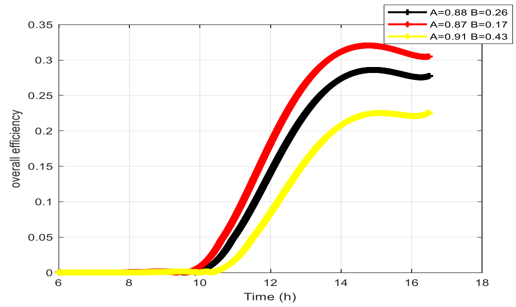


Fig. 6: Evolution of Overall Efficiency.

It begins to evolve at 10 a.m. and then increases rapidly over the hours. The maximum values are reached around 3 p.m. They are 32%, 28.6%, and 22.4% respectively for a clear sky (A=0.87, B=0.17), for a sky under normal atmospheric conditions (A=0.88, B=0.26), and for a polluted sky (A=0.91, B=0.43). The highest value is obtained for a clear sky condition. This is due to the clarity of the sky. The more solar radiation reaches the concentrator, the greater its overall efficiency. The overall efficiency, therefore, evolves according to the sunshine. Our results agree with those of N. Boukerzaza [20], who studied the influence of irradiation on the operating characteristics of a spherical still.

3.5. Impact of the nature of the sky on internal efficiency

Figure 7 shows the evolution of internal efficiency. It has a similar pattern to that of overall efficiency.

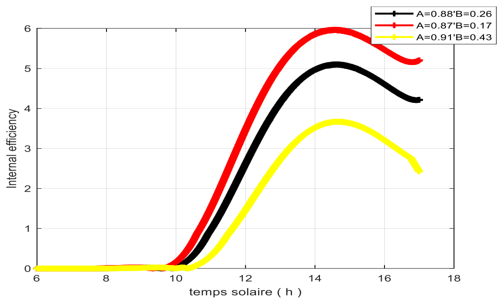


Fig. 7: Evolution of Internal Efficiency.

It is higher than the overall efficiency. This is explained by the fact that internal efficiency is the ratio of the amount of evaporation heat to the solar power absorbed by the water, while overall efficiency is the ratio of the amount of evaporation heat to the irradiation. It begins to change from 10 a.m. and then increases over the hours until 3 p.m. The maximum values are 5, 6, and 3.5, respectively, for a sky with normal atmospheric conditions (A-0.88, B-0.26), a clear sky (A-0.87, B-0.17), and a polluted sky (A-0.91, B-0.43). The highest value is obtained for a clear sky, which is explained by the fact that the amount of heat used for evaporation is very high for a clear sky. Our results are like those of N. Boukerzaza and A. Delliou.

3.6. Impact on exergy efficiency

Figure 8 shows the evolution of exergy efficiency as a function of sky conditions.

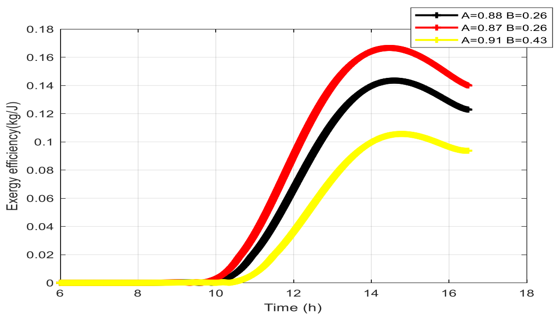


Fig. 8: Evolution of Exergy Efficiency.

It begins to evolve at 10 a.m. and then increases rapidly between 10 a.m. and 2 p.m., reaching its maximum value around 3 p.m.; then it begins to decrease. The maximum values obtained are 0.16, 0.145, and 0.105, respectively, for a clear sky (A=0.87, B=0.17), for normal atmospheric conditions (A=0.88, B=0.26), and for a polluted sky (A=0.91, B=0.43). It can be noted that the highest exergy efficiency is that of a clear sky. We can conclude that the exergy efficiency of our device evolves as a function of sunlight.

4. Conclusion

As part of our work, we studied the impact of sky conditions on the operation of a concentrated solar still. We presented its impact on productivity, overall, internal, and exergy efficiency. We observed that the best performance of the still is obtained for a clear sky, then for a sky with normal atmospheric conditions, and finally for a polluted sky. This is explained by the fact that sunshine is very high for a clear sky, then for a sky with normal atmospheric conditions, and finally for a polluted sky. Given the results, we can affirm that productivity, overall, internal, and exergy efficiency are a function of sunshine. The analysis of solar radiation for the three types of sky allows us to say that for proper operation of the device, it must be placed in a region with strong sunlight. We note that even for a polluted sky, we have significant maximum productivity; we can thus affirm that our device is efficient. In the rest of our work, we will proceed with the construction of the device, where the concentrator will be equipped with a sun tracking system to improve the performance of our device even under a polluted sky, and with the experimental study to validate the numerical model.

Nomenclature

A Glass surface area (m²)

C Specific heat (J/kg °C)

C_g Geometric concentration coefficient

e Glass thickness (m)

$Exer$ Exergy (W/m²)

Fp Performance factor (J/kg C1

G_r Graschoff number

h Heat transfer coefficient (W/m²C)

I Absorbed solar power (W/m²)

I Radiation, global (W/m²)

L Length (m)

I Specific heat of vaporization (J/kg)

M Mass (kg)

m_d Mass flow rate (kg/m h)

P Partial Vapor Pressure (P)

P_r Prandtl Number

Q Heat Flux (W)

T Temperature (°C)

t Time (S)

V Wind Speed (m/s)

Greek Letters

α Absorption Coefficient

β Tilt Angle

ε Emissivity

φ_1 The diffuse flux emitted by the celestial vault (W/m^2)

φ_2 The flux emitted by the ground (W/m^2)

λ Thermal Conductivity ($W/m°C$)

η Efficiency

σ Blozman Constant

ρ Reflection Coefficient

τ Transmission Coefficient

Abreviation

a Ambiant

abs Absorber

CVA Glass-ambient convection

CVE Glass-water convection

D Direct
d diffuse

E Water

EV Evaporation

f Fluid

g Global

RVE Glass-water radiation

RVA Ambient glass radiation

vex Outer glass

vin Inner glass

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