Numerical Approach of a Double Slope Solar Still Combined with a Cylindrical Solar Water Heater: Mass and Heat Energy Balance Mathematical Model

Omar BAIT[1*], Mohamed SI-AMEUR[1], Abdelaziz BENMOUSSA[1]
[1] University of Batna, Department of Mechanical Engineering, 05000 Batna, Algeria

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ABSTRACT

Solar desalination field is known by its large area among the developed science technologies. It has the most favor to produce pure water to overcome the water needs issue in arid regions. For this reason, several researches were undertaken a local manufacturing devices which can realize this objective. The focus of this article is to discuss a new approach of solar distillation system. The aim is to combine a double slope solar still with a cylindrical solar water heater which can be motivated by the two following significant reasons: firstly, to increase water temperature inside the solar still in order to improve with, high level, its distillate production capability, besides, the cylindrical type solar heater has a good ability of heating water with low heat losses to the ambient surrounding. Both of the previous systems may form a double slope active solar still. Performed numerical investigations are based on the determination of temperature and distillate mass profiles in the case of an active solar still and to compare them to those of solar still without preheating system. The computer program has been elaborated in this study using Fortran 6.6 language as an investigation platform to examine temperature and mass production parameters. Simultaneously, temperature increasing and mass production have been computed through the active solar still and compared to the uncoupled system (passive solar still). Results show clearly an increase of temperature and distillate mass production by 8.94 °C and 0.67 kg/m^2/day respectively.

Keywords: Distillation, Solar Water Heater, Solar Stills, Distillate production

1. INTRODUCTION

Conducted researches on solar stills have generally made revolution in this field according to the significant successive innovations of these engineering devices which have recently been studied extensively due to availability of local materials. The aim is to produce potable water especially for the remote areas suffering of rarity of this precious substance. Less than 1% of the earth's fresh water is within human reach for drinking and agriculture purposes [6]. Indeed, the percentage value presented previously show a real acute shortage which is effectively not sufficient and cannot meet due to growth of the population, agricultural and industrial applications. The apparition of solar stills which are efficient economically with a simple technology has reversed balances in human life for the best horizons like the other advanced or modern technologies and with their manifestation in several countries recently. They are considered among the crucial keys which respond to potable water needs especially in rural or arid regions. A great focus may catch us that these devices have an important potential to produce distilled water by the utilization of an available, efficient and free energy source which is solar energy. Stills are small enclosure box systems which work similarly as evaporation and condensation natural cycle.

They consist on a basin containing salt water, which has role as an evaporation surface and plastic or transparent glass materials as a condensation surface and finally, gutters for the collection of distillate.

The operating process begins by the transmission of solar energy inside the enclosure system through a transparent inclined surface to reach the water in basin. With time, water has tendency to heats up, evaporates and condenses on the inner surface of the transparent cover. Condensed water is conducted directly to collection in a separate tank.

In the following contexts, whether, the two large categories of solar stills were either performed passively or actively situations are well known by several works which have thoroughly been attracted to investigate them intensively. The first studied category were passive stills. A novel approach of solar still has been performed by Rajaseenivasan et al. [1]. Obtained results reveal that 85% of production of double basin still is higher than a single basin still. El-Sebaey et al. [2] fabricated and tested a new design of double slope still with internal parabolic and external flatted reflectors for Egyptian climatic conditions. They have found that optimum tilted angle and maximum daily productivity are respectively 60° and 9.89 liter/m^2. A double slope still has been investigated using two mathematical models, constructed and furthermore tested by Murugavel et al. [3]. Results show an agreement between both mathematical modeling and experiments. A simple basin double slope still has been constructed, operated and also mathematically modeled by

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[*] *Sorumlu Yazar (Corresponding Author)*
e-posta: obait80@yahoo.fr
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Murugavel et al. [4]. Water basin contains different materials in order to have information about the performance with the presence of these ingredients. Hemispherical solar still system has been carried out by Arunkumar et al. [5]. In the case of cooling hemispherical cover, the new configuration has an efficiency of 42%.

In the second wave, new solar still systems have been performed in order to enhance distillation production, which are known by active stills category. Numerical investigation of Sampathkumar and Senthilkumar [6] is based on the combination of a basin still with a preheating system. It is shown a 77% of yield and an augmentation in water temperature achieved 60 °C. Rai and Tiwari [7] have presented a study around a combination of solar still with a flat-plat collector. It was found that the coupled system can produce 24 % greater than an uncoupled still. An interesting investigation study has been attributed to Sanjay and Sinha [8] which it demonstrates that a concentrator combined with still has given a high distillate production. A distillation film behavior has been analyzed by Morcos [9] in the case of solar collector combined with a solar still. Found results show that the coupled system with a collector and the influence of the basin painted black, give a good yield. Experimental study has been conducted by Zaki et al. [10] on solar still integrated with concentrator. The obtained results illustrate 22% of yield using a preheating system. Whereas, Dwivedi and Tiwari [11] studied experimentally and validated mathematically a double slope still under natural circulation mode coupled with solar collectors. Investigations show that, thermal efficiency of active double slope still is low than that of the double slope passive still.

Our choice to combine specifically a cylindrical solar water heater with such distillation system as double slope solar still is based on the experimental study of Al-Madani [12] which he has designed and constructed this type of solar heater in the University of Bahrain. 41.8% is the efficiency value of this solar heater.

Other work was effectuated by Ogueke et al. [13] which they have made the design, the construction and moreover a performance testing on cylindrical solar water heater preheating system. Results show maximum efficiencies were obtained respectively as follow: 57.09%, 53.99% and 56.21%, for every mass flow rates of 3.6, 7.2, and 10.8 kg/h. Bait et al. [14] have simulated mathematically transient processes of cylindrical solar water heater. Numerical simulations have been carried out in order to estimate efficiency in different situations. Results have been confronted to experimental measurements available in open literature.

Among researches presented previously which have been carried out to show clearly the possibility of coupling distillation systems with flat-plat solar collectors. However, flat-plat collectors present disadvantages which are unfortunately, expensive and require specialists in maintenance, and therefore, it is very important to construct a mechanism with low spending. The present paper may illustrate the following: utilization of double slope solar still is evidently due to its considerable high production of condensate, because it represents a geometrical design improvement of the previous constructed system regarding the single slope solar still. Thus, due to their simplest design, passive stills suffering of lowest production of distilled water. Furthermore, the chosen preheating system, cylindrical solar heater represents a new generation in solar collectors field and it has the ability to heat up the water with low heat losses to the surrounding environment. On the other hand, it is recognized by its simple and reliable design, having the advantage of taking a small area and it does not need to be oriented to the sunlight. All these relevant characteristics which may make it easily constructed. Analysis by mean of numerical simulations of both temperature and distillate mass production evolutions for this new type of solar distillation system which has been designed using SolidWorks software is the main purpose of this work. A great attention has been contributed that all numerical computations have thoroughly been performed for a location in Batna city (35°33 ′N, 6°11 ′E) situated in the North East of Algeria, and characterized by a semi–arid climate. The objectives desired from the present study are:

- Exploration of this new solar distillation system,
- Presentation of its governing mathematical model and,
- Determination of temperature and distillate mass production fields based on thermal model of double slope active solar still under natural circulation mode.

The present treated issue was chosen to be thoroughly conducted by the use of numerical investigation which provides an efficient tool allowing us to perform easily and effectively any problem with low costs and gain in time and moreover, it can solve stagnation issues confronted in developed experiments. Whereas, experimental processes may consume in time and increasing costs. The manuscript may take the following organization: in section (1), both statuses of the art of different solar stills devices performed in the past and recently and the proposed system, have been presented. In section (2), we will describe this new solar still type as well as its suitable operating process. In section (3), a mathematical model has been applied for the present system. Section (4) is dedicated for various results of our numerical simulations, and then a conclusion including the main reaching results which forms the main objective of the last section.

2. DESCRIPTION OF THE SYSTEM AND OPERATING MODE

Figures (1. a), (1. b), (1. c) and (1. d) represent clearly the global system designed using SolidWorks software which consists of the following principal components, namely, the double slope solar still (Fig.1. a) and a cylindrical solar water heater (Fig.1. b). The system has the following simple operating process: initially, a spiral tube existing inside the solar water heater which is generally painted black to absorb a maximum incident solar energy, heats up the supplied saline water passing through (Fig.1. c). The preheating system is directly exposed to the sunlight and due to its cylindrical shape it does not need to be inclined to the horizontal. Note that the present system is chosen to work under natural circulation mode (without pumping system) to minimize fabrication costs. On the other hand, the use of pumping system prevents reheating of the circulating fluid due to its considerable flow velocity. The heated water gets to the solar still from the solar water heater by the mean of an insulated tube as shown in figure 1. d. Besides the energy received by water inside the solar still from the incident solar energy, the water may receive a supplement energy while passing through the solar water heater. Because of the difference of temperatures between saline water in the basin and the condensation surface (the cover internal surface), water has tendency to evaporate. Hence, the evaporated water condensates in contact of the cool cover internal surface. Distillated water slides inside the inner surface of the glass cover due to both gravity effect and inclination of the transparent cover surface, towards collection in a separate tank through gutters installed in inner sides of the distillation system (Fig.1. c and Fig.1. d)

3. MATHEMATICAL GOVERNING MODEL

The set transient energy balance equations system applied for the three main components of the double slope solar still namely, the basin, the water and the transparent cover is totally inspired on the base of the work mentioned through the reference [15]:

Firstly, transient energy balance equation for the basin component is given by:

$$A_b \times AB_b \times H_t = m_b \times cp_b \times \frac{dT_b}{dt} + Q_{c,b-w} + Q_{loss} \tag{1}$$

Secondly, it may be written for the saline water as:

$$A_w \times AB_w \times H_t + Q_{c,b-w} = m_w \times cp_w \times \frac{dT_w}{dt} + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} \tag{2}$$

Thirdly, it is expressed for the glass cover as:

$$A_g \times AB_g \times H_t + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} = m_g \times cp_g \times \frac{dT_g}{dt} + Q_{r,g-sky} + Q_{c,g-sky} \tag{3}$$

3.1. Expressions Of Different Heat Fluxes

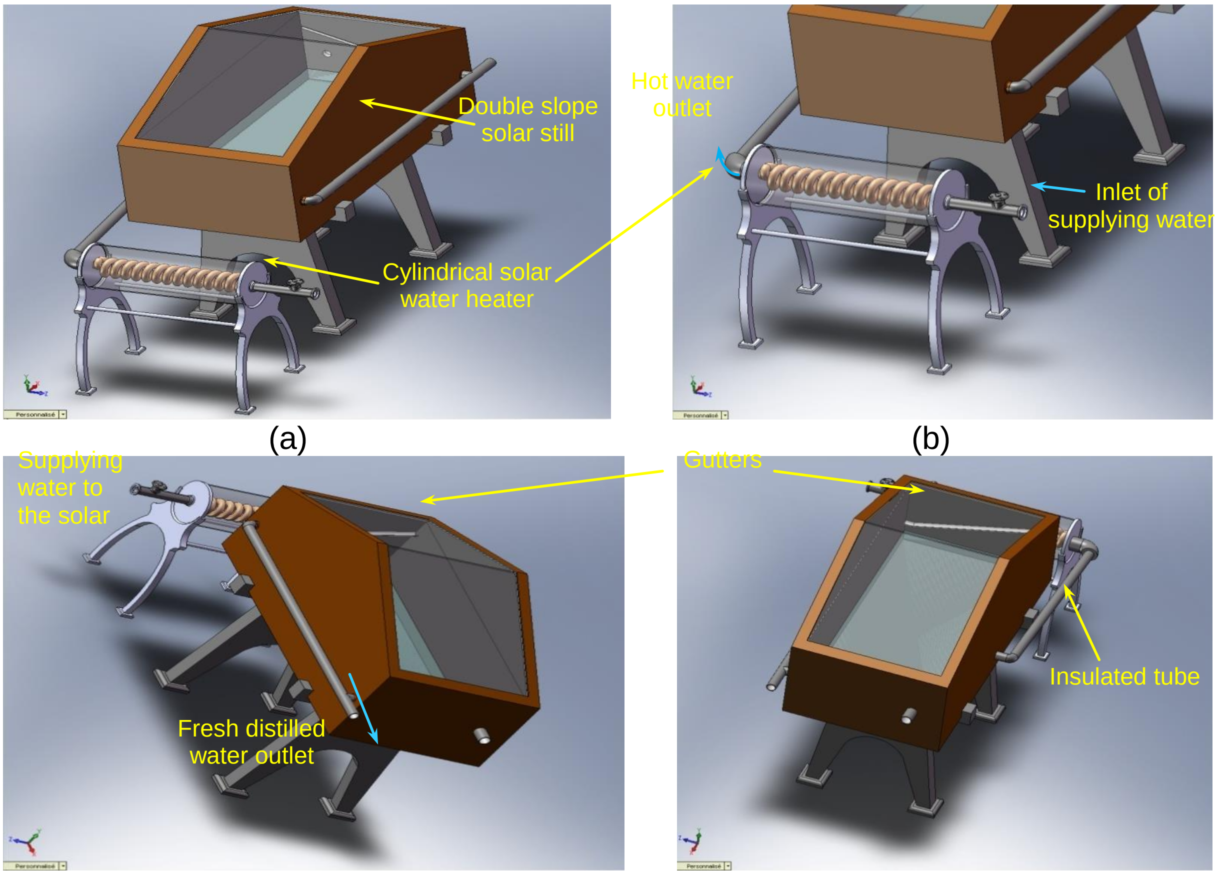

Figure 1- (a) Global combined systems (b) Cylindrical solar water heater (Preheating system) (c,d) Circuit of conduits

According to the mathematical equations modeling the different parts of the double slope solar still, each Q_i energies are presented as follows:

Convective heat flux between the basin and the water is:

$$Q_{c,b-w} = h_{c,b-w} \times A_b \times (T_b - T_w) \tag{4}$$

Convective heat flux between the water and the glass cover is:

$$Q_{c,w-g} = h_{c,w-g} \times A_w \times (T_w - T_g) \tag{5}$$

Radiative heat flux between the water and the glass cover is:

$$Q_{r,w-g} = h_{r,w-g} \times A_w \times (T_w - T_g) \tag{6}$$

Evaporative heat flux between the water and the glass cover is:

$$Q_{e,w-g} = h_{e,w-g} \times A_w \times (T_w - T_g) \tag{7}$$

Radiative heat flux between the glass cover and the ambient is:

$$Q_{r,g-sky} = \sigma \varepsilon_g A_g \left((T_g + 273.15)^4 - (T_a + 273.15)^4 \right) \tag{8}$$

Convective heat flux between the glass cover and the ambient is:

$$Q_{c,g-sky} = h_{c,c-sky} \times A_g \times (T_g - T_{sky}) \tag{9}$$

Convective heat loss between the basin and the ambient is:

$$Q_{loss} = U_b \times A_b \times (T_b - T_a) \tag{10}$$

3.2. Expressions Of Different Heat Transfer Coefficients

Different h_i heat transfer coefficients mentioned in each previous Q_i energies expressions are illustrated explicitly in the following formulas.

Convection heat transfer coefficient between water and glass cover is given as:

$$h_{c,w-g} = 0.884 \left(T_w - T_g + \frac{(P_w - P_g)(T_w + 273.15)}{268.9 \times 10^3 - P_w} \right)^{\frac{1}{3}} \tag{11}$$

Radiation heat transfer coefficient between water and glass cover is given as:

$$h_{r,w-g} = \varepsilon_{eff} \times \sigma \times \left(\frac{(T_w + 273.15)^4 - (T_g + 273.15)^4}{T_w - T_g} \right) \tag{12}$$

Evaporation heat transfer coefficient between water and glass cover is given as:

$$h_{e,w-g} = \frac{M_w h_{fg} P_T}{M_a cp_a (P_T - P_w)(P_T - P_g)} h_{c,w-g} \tag{13}$$

Convection heat transfer coefficient between glass cover and the ambient is given as:

$$h_{c,g-sky} = 2.8 + 3 \times V \tag{14}$$

Partial pressure of the vapor is given by the following correlation:

$$P = 7235 - 431.43T + 10.76T^2 \tag{15}$$

Latent heat of water is given by the following expression:

$$h_{fg} = 1000 \times (2503.3 - 2.398T) \tag{16}$$

Specific heat of air is estimated with respect to the average temperature between the basin and the glass cover. Its following expression is given by:

$$\begin{aligned} cp_a = 999.2 &+ (0.14339 \times T_{av}) + \\ &(0.0001101 \times T_{av}^2) - \\ &(0.000000067581 \times T_{av}^3) \end{aligned} \tag{17}$$

Absorptances for different media are given as:

- For the basin component:

$$AB_b = (1 - \rho_g - AB_g - AB_w) \alpha_b \tag{18}$$

- For the water:

$$AB_w = (1 - \rho_g - AB_g) \alpha_w \tag{19}$$

And for the transparent glass cover:

$$AB_g = (1 - \rho_g) \alpha_g \tag{20}$$

3.3. Main Governing Expression for Double Slope Solar Still Combined With Cylindrical Solar Water Heater

Detailed explanation of the system presented previously may be completed through a mathematical investigation explicating clearly the role of coupling solar water heater cylindrical type with solar still double slope. We highlight by energy balance equation established below, which is specifically governs the double slope solar still combined with cylindrical solar heater. The main energy expression may be illustrated as:

$$\begin{aligned} A_w \times AB_w \times H_t + Q_{c,b-w} + Q_u = \\ m_w \times cp_w \times \frac{dT_w}{dt} + Q_{c,w-g} + \\ Q_{r,w-g} + Q_{e,w-g} \end{aligned} \tag{21}$$

Equation (21) is funded evidently on the base of the equation (3) including the Q_u energy. Therefore, the Q_u term appearing in equation 21 is given in literature by the reference [16]. It can explicitly be explained by the rate of thermal energy (the useful energy gained) available from the preheating system (cylindrical solar water heater). In its turn, Q_u can be expressed as the product of solar collector area A_{col} times the F_R collector heat removal factor times the difference between the absorbed solar radiation S by the basin and transmitted through the transparent glass cover which represents the energy getting from the sun and the product of U_L $(T_f - T_a)$ term. The Main equation of Q_u thermal energy may be written as:

$$Q_u = A_{col} q_u = A_{col} F_R [S - U_L (T_f - T_a)] \qquad (22)$$

3.4. Resolution Procedure of the Set Equations

After a general presentation of the art status of the system and its corresponding theoretical mathematical model, we will seek a basic methodology to solve the present problem, which can track the following steps in order to predict both temperature and distillate mass production fields. As first step, a program was written using FORTRAN language, and elaborated in which, equations (11) to (20) followed by equations (4) to (10) were firstly implemented. As second step, equations (1), (2), (3) and (21) should firstly be arranged according to the general ordinary differential equations format figured below in equation (23) and then solved utilizing the 4th order Rung-Kutta method which represents an adequate numerical method for these typical equations.

$$\frac{dT_i}{dt} + aT_i = f(t) \qquad (23)$$

The T_i is the unknown parameter of the equation (23) which represents successively in our case the basin or the water or the transparent glass cover temperatures and a is a constant which is function of different heat transfer coefficients. Finally, $f(t)$ is function of time. Before starting computation process (Loop time), an initial value must be injected. Furthermore, thermal proprieties should evidently be added to program which are obviously shown in the below table (Tab. 1) to reach the desired objective from the program which is obtaining information around simultaneously, temperature and distillate amount of the double slope active solar still

Table 1- Physical properties [2]

Properties	Basin	Glass Cover	Water
Area (m^2)	1.08	0.7056	
Absorptivity (-)	0.95	0.05	0.0475
Specific heat capacity (J/kg K)	473	800	4187

4. RESULTS AND DISCUSSION

4.1. Temperatures Field of the Double Slope Active Solar Still

Comprehension of numerical solutions sets may give to the reader information around temperatures and distillate mass production curves. Firstly, it is appearing clearly in figure 2 the temporal variations of temperature which are plotted in a clear day, for the basin, water and transparent glass cover components. It can be note that temperatures of each components have the following tendency: initially, they increase gradually along with the sunset even its maximum corresponding to the midday and then will decrease with the sunset which can lead to think in solar radiation curves, which it reveals that both temperatures and solar radiation behavior with the same trend. During the daylight which can be divided in three main intervals time, in the first interval (between 5:00 a.m. and 9:00 a.m.), the still receives solar radiation with low intensity till it takes to be more intense in the second interval (between 10:00 a.m. and 14:00 a.m.) hence, components temperature are high. Beyond 14:00 a.m. which represents the third interval in which solar radiation is less intense and this consequently leads to low components temperature of the still.

The basin component is the main part of the still which can play an important role of an evaporation surface. It represents an enclosure box configuration covered in black which it is able to absorb a maximum solar radiation. According to the graph below, which indicates that both basin and water temperatures increases gradually and they may achieve their maximum value of 91.26 °C and 75.06 °C at 1:00 a.m. period corresponding a high solar radiation intensity reaching 928.79 W/m^2. Between 12:00 a.m. and 2:00 p.m. it can be observed that temperature curves remain almost stable and this implies that there is no significant temperature variation.

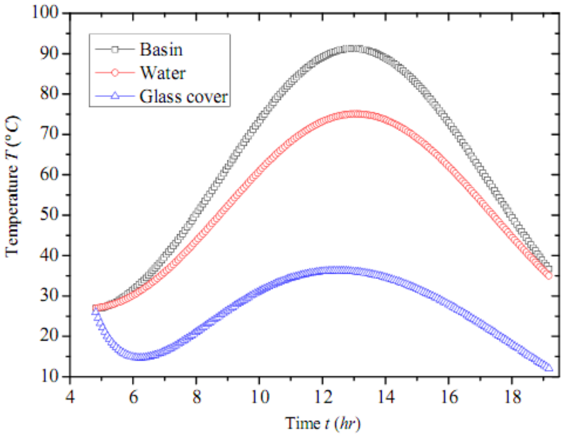

Figure 2- Temperature profiles evolution of each part of active distillation system

Moreover, it is evidently that water temperature is slightly smaller than that of the basin due to its significant thermal physical proprieties which are: high thermal conductivity, low coefficient of transmittivity and relatively high absorption of the black paint. The same figure shows also the transparent glass cover temperature evolution as a function of time which gradually increases due to the heat flux transferred by evaporation of salt water inside the solar still and by natural convection and radiation outside the one. Glass cover temperature is lower than those obtained of the basin and water. Its profile is located below them.

4.2. Temperatures Field Comparison Between Passive And Active Solar Distillation Systems

In order to show obviously the capacity of the proposed system, we have conducted numerical simulations examining a comparison between a double slope active solar still and passive one which they operate in the same working conditions and which are clearly illustrated schematically appearing in figure 3. It can be seen, during the distillation process, for the passive system which can distill salt water until a maximum temperature reaching in the middle of the day by 66.12 °C, whereas, the active one, can distill salt water more than that obtained by the passive system which can reach 75.06 °C for the same insolation period. Consequently, it is easy to note an increase of 8.94 °C of temperature. As well as, comparisons show additionally basin temperature fields. In the case of an active performed system, its corresponding basin temperature can achieve 91.26 °C however it can reach 83.31°C for the passive system. A numerical gap value of 7.95 °C is the temperature augmentation. From the same graph and in the end of the day, temperatures of each part of the active still are considerably greater than the passive solar still. For the former, it can continue to distill salt water even after sunset because of the stored energy provided by the preheating system.

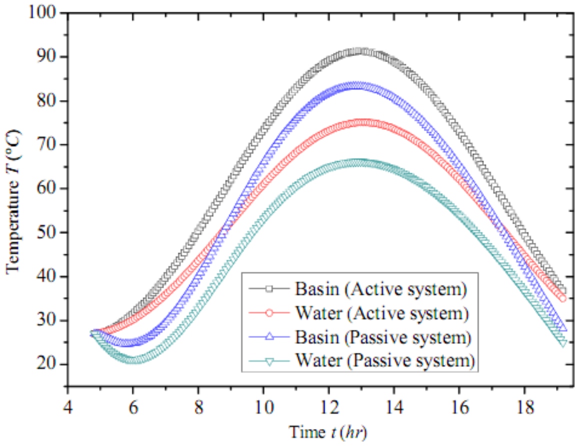

Figure 3- Comparison between the active and passive solar still systems

4.3. Cumulative of Mass Production for the Passive And Active Distillation Systems

Another important parameter characterized a solar still is its distillate production capacity. This parameter has been carried out numerically in order to have information around the distillated water mass from the proposed system which can produce it. The figure 4 highlights by mean of sketch the condensate amount curve for both the present system and the passive solar still. It can be easily read from the graph that the maximum distillate production in the case of a small thickness of salt water inside both of the active and passive systems, is evidently occurred by the double slope active solar still which can give a significant rate per day of 3 kg/m^2/day, whereas, the second system, its production capacity can achieve 2.33 kg/m^2/day. An increase has been observed by 0.67 kg/m^2/day of mass production rate. Numerical obtained value of mass distillate for the active still can be compared to that reached experimentally by several researches, for example: Dwivedi and Tiwari [11] have conducted a study of a double slope solar still coupled with a flat-plat collector and they have found that the coupled system has a capability to produce distilled water of 2.791 kg/m^2/day. Furthermore, Sanjay and Sinha [8] have studied different cases of a double slope solar still combined, in one time, with a collector and for another time with a concentrator. It was found that in the case of a collector combination which may achieve 8 l/m^2/day of distillate mass production, whereas, for the concentrator coupling, it is slightly greater than the collector combination production quantity. All these significant differences can be explained by the reason of the deep difference in the meteorological coordinates of the local and also the working climatic conditions of the systems. A remarkable point, for both of the two systems, their production capability can be noticed when temperature is highest which corresponds high solar radiation intensity.

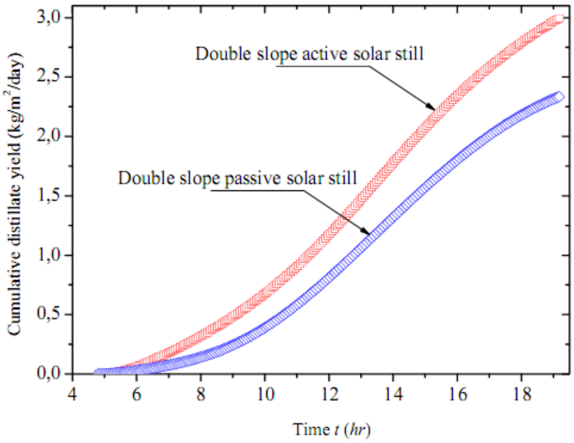

Figure 4- Cumulative of hourly distillate yield for both passive and active solar stills

5. CONCLUSION

Solar stills have a large various proposed geometric configurations with a simple technology design which can be classified as sustainable and efficient devices that use a clear energy source to reach directly the principal aim which is production of drinkable water with low spending. Different conceptions of stills have deeply been carried out both numerically and experimentally to provide information around their own performance. Among them, we confronted by the double slope solar stills which are known by their several significant benefits. They can produce a considerable distilled water amount compared to that of single slope stills. In this work, we have proposed to investigate by mean of numerical simulations a new type of active solar distillation system under Batna climate conditions, namely, the coupling of a double slope solar still with a cylindrical solar water heater which is thoroughly designed by SolidWorks as tool of conception to give us a clear view on the principal different components constituting the global system. Comparisons of both temperatures and condensate production fields between passive and active solar stills have been performed and also graphically illustrated. Results show that the proposed enhancement conception of the passive solar still by combination with the present preheating system (Cylindrical solar water heater) has relevantly improved its capacities namely the temperature and mass rate distillate production. In the passive situation it was found 66.12 °C of heating water temperature, on the other hand it is increased reaching 75.06 °C which represents a important augmentation difference by 8.94 °C. The second investigated parameter regarding the distillated water amount for the two devices was also taken into account. The uncoupled design (passive still) has the ability to produce a condensate amount which can reach 2.33 kg/m^2/day at the end of the distillation process, while for the second system active still was considerably higher and it can achieve its maximum value of 3 kg/m^2/day which it can be evidently seen a difference of 0.67 kg/m^2/day of produced distillate quantity.

6. NOMENCLATURE

A	Area, m^2
AB	Absorptance
Cp	Specific heat, J/kg °C
Cp_a	Specific heat of air, J/kg °C
F_R	Collector heat removal factor
h_c	Convection heat transfer coefficient, W/m^2 K
h_e	Evaporation heat transfer coefficient, W/m^2 K
h_{fg}	Water latent heat, J/kg
h_r	Radiation heat transfer coefficient, W/m^2 K
H_t	Solar radiation intensity, W/m^2
m	Mass, kg
P	Partial pressure, N/m^2
Q_c	Convective heat flux, W/m^2
Q_e	Evaporative heat flux, W/m^2
Q_{loss}	Convective heat loss, W/m^2
Q_r	Radiative heat flux, W/m^2
Q_u	Useful gain energy, J
S	Absorbed solar radiation, W/m^2
t	Time, s
T	Temperature, °C
U_b	Heat loss coefficient, W/m^2 °C
U_L	Overall heat loss coefficient, W/m^2 K
V	Velocity of wind, m/s

Greek symbols

α	Absorptivity
ε_{eff}	Effective emissivity
ρ	Reflectivity
σ	Stefan-Boltzmann coefficient

Subscripts

av	Average
col	Collector
b	Basin
f	Fluid
g	Glass cover
w	Water

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