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Theoretical and Experimental Investigation on the Influence of Still Glass Cover Cooling on Water Productivity.

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THEORETICAL AND EXPERIMENTAL INVESTIGATION ON THE INFLUENCE OF STILL GLASS COVER COOLING ON WATER PRODUCTIVITY

دراسة نظرية وعملية لبحث تأثير تبريد السطح الزجاجي للمقطر الشمسي على الإنتاجية

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خلاصة:

يقدم هذا البحث دراسة نظرية وعملية لعملية تبريد السطح الزجاجي للمقطر الشمسي حيث تتم الدراسة عند الكميات المختلفة من ماء التبريد ويعاد جزء من هذا الماء الى المقطر ليستخدم في عملية تعويض الماء المبخر من المقطر . تم إنشاء مقطرين شمسين لهم نفس الشكل والأبعاد بكلية الهندسة جامعة طنطا, حيث يتم تبريد السطح الزجاجي للمقطر الأول ويستخدم المقطر الثاني للمقارنة. تم دراسة أداء المقطر عند قيم مختلفة من ماء التبريد وتم استنتاج انسب كمية تبريد يمكن استخدامها عند الظروف المختلفة. أوضحت النتائج النظرية والعملية أن الأداء يتحسن بتبريد الغطاء الزجاجي للمقطر وتعتمد هذه الزيادة على كمية التبريد وتصل أقصى نسبة زيادة الى ٦٠ ٪.

Abstract

This paper presents a theoretical and experimental investigation on the optimization of a solar still. The theoretical approach is based on the simulation of the solar desalination system, the influenced parameters were isolated and their corresponding effects were numerically evaluated. According to these results, the optimization methodology is based on the concept of recuperation of the condensed heat. Two solar stills having the same dimensions were constructed. A descending film of salt water cools the glass cover of the first still. The cooling water is then recycled and fed into the supply of the solar still. The other still is simple and conventional, it is used only for comparison and reference purpose. Both stills are similar in geometry, and inclination angle. The theoretical and experimental results show that the productivity increase with cooling the glass cover. The experimental results show important increment in productivity, reaches in some cases 60 %. The influence of cooling water flow rate was also investigated. The experimental investigation has shown the non-linear behavior of the flow rate on the performance.

The objective of the present research work is to reach an optimum system configuration in order to provide a simple and high effect solar distillation unit.

Introduction

The increasing population, coupled with the industrial and agricultural development of rural areas are creating an unbalance between supply and demand. The recourse to non-conventional water resource is a must in order to respond to this situation. The desalination of brackish and seawater is suitable solution for many cases. The desalination technologies have reached an advanced commercial maturation stage, which put it as a potential competitor to other low price water treatment technologies. Various types of desalination plants have been built and developed world wide, according to recent IDA inventory more than 17 millions litter/day is desalting around the world. However, most existing desalination units use fossil fuels as a source of energy.

Modern civilization is completely depending on the cheap and abundant energy. The economic wealth and material standards of living of a country are determined by the technologies and fuels which are available. The cost of energy has shown to be a major component of the cost of distilled water. The actual low price of fossil energy sources, have encouraged the dependents on fossil energy. The solar has a definite advantage over the fossil, which is its adaptability for small stand-alone units in rural and isolated areas.

Solar stills, in many cases, might be an ideal source of fresh water for drinking and agriculture, in arid isolated zones. The first conventional solar still (4700 m^2 in area) was built in 1872. Since then a great number of researches, as well as excellent monographs has been published [1], [2]. Recently [3],[4] and [5] a different model has been presented. The basic idea is how to recycle the recuperated heat from the vapour condensation. Gyorgy et al [7] has presented a scheme based on the air blown method for heat recycle. In the present investigation the improvement methodology is based upon the cooling of still glass cover with a thin layer of saline water before its introduction into the solar still.

The effect of cooling water flow rate on productivity was also studied at different amount of cooling. A simple theoretical model is used for the solution of the general equation. A finite difference numerical technical is used for the solution of the governing equation. A comparison between the theoretical model results and experimental results is presented. The results have shown reasonable agreement between theoretical and experimental findings.

The objective of this research is to improve the solar still productivity through the modification of the system configuration, based on energy recovery approach.

Formulation of the Problem (Theoretical model)

The theoretical model depends on the energy balance of each part of the system The following assumptions have been assumed:
1-There is no leakage in the still.
2-The temperature gradient across the cooling water film, the glass cover thickness and water depth have been assumed negligible.
Energy balance of cooling water and glass cover are calculated from the following equations:

$$M_{cw}\left(T_{cwo}-T_{cwi}\right)+h_{2}\left(T_{g}-T_{cw}\right)-h_{3}\left(T_{cw}-T_{a}\right)+\alpha_{cw}H_{s}=0 \tag{1}$$

$$M_{g}\frac{dT_{g}}{dt}=\tau_{1}\,H_{s}+h_{1}\left(T_{w}-T_{g}\right)-h_{2}\left(T_{g}-T_{cw}\right) \tag{2}$$

where

$$\tau_{1}=\left(1-R_{cw}\right)\left(1-\alpha_{cw}\right)\alpha_{g} \tag{3}$$

h_{1}, is combined convective, radiative and evaporative heat transfer coefficient from water to glass cover still, ($W/m^{2}C$) and h_{2} is heat transfer coefficient from glass cover to cooling water ($W/m^{2}\,C$) and h_{3} is heat transfer coefficient from cooling water to ambient air, ($W/m^{2}C$)

Energy balance of water content in the still basin can be expressed as:

$$M_{w}\frac{dT_{w}}{dt}=\tau_{2}H_{s}-h_{1}\left(T_{w}-T_{g}\right)-h_{4}\left(T_{w}-T_{b}\right) \tag{4}$$

where:

$$\tau_{2}=\left(1-R_{cw}\right)\left(1-\alpha_{cw}\right)\left(1-\alpha_{g}\right)\alpha_{w} \tag{5}$$

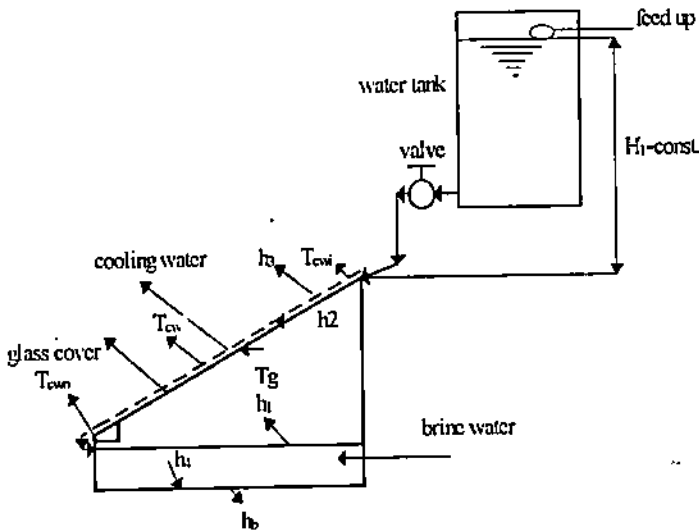H_{s} = total solar radiation on the still, (W/m^{2})

Fig. (1): Flow diagram of the solar distillation system

Energy balance of the basine liner can be expressed as:

$$\tau_{3}H_{s}=h_{4}\left(T_{b}-T_{w}\right)+h_{5}\left(T_{b}-T_{a}\right) \tag{6}$$

where:

$$\tau_{3}=\left(1-R_{cw}\right)\left(1-\alpha_{cw}\right)\left(1-\alpha_{g}\right)\left(1-\alpha_{w}\right)\alpha_{b} \tag{7}$$

$$\frac{1}{h_b} = \frac{t_1}{K} + \frac{1}{h_s} \qquad (8)$$

h_4 is   heat transfer coefficient from the saline water to the basin liner, $(W/m^2 C)$ and h_s is heat transfer coefficient from the bottom of insulation to ambient air, $(W/m^2 C)$ and h_b is overall heat transfer coefficient from the bottom to the ambient, $(W/m^2 C)$.
Substituing the value of T_b from equations (6) in equation (4), one obtains

$$M_w \frac{dT_w}{dt} = \tau_4 H_s - h_1\left(T_w - T_s\right) - U_b\left(T_w - T_a\right) \qquad (9)$$

where:

$$\tau_4 = \tau_2 + U_b\left(\frac{t_1}{K} + \frac{1}{h_s}\right)\tau_3 \qquad (10)$$

$$\frac{1}{U_b} = \left(\frac{1}{h_4} + \frac{1}{h_b}\right) \qquad (11)$$

To calculate the thickness of the film of the cooling water, assuming laminar flow

$$V_x = \frac{g\sin\theta}{\upsilon}\left[t.y - \frac{y^2}{2}\right]$$

The volume flow rate of the cooling water is calculated from the following relation:

$$Q = \int_0^t V_x b.dy = \frac{g\sin\theta}{\upsilon}\cdot\frac{t^3}{3}.b \qquad (12)$$

The thickness is calculated from the following relation:

$$m = \frac{\rho g\sin\theta}{\upsilon}\cdot\frac{t^3}{3}.b \qquad (13)$$

where: m is the cooling water flow rate, (kg/sec), t is the thickness of cold water and b is the still width

The absorbtivty and reflectivity of the cooling water will   change with the film thickness of the cooling water, there are poor information about the small thickness. The only avaible data is presented in the follwing table [6].

water thickness (t), m	0.1m	0.5m	1.0m	1.5m
absorbtivity reflectivity product	0.541	0.384	0.322	0.301 Kw/m²

In the present work, the cooling water layer   thickness is less than 0.1 m. A linear relation is assumed, in order to retrieve the necessary data of aborbtivty and reflectivity for small thickness ranging from zero   to   0.1 m. It is assumed that the absorbtivty thickness and if assumed that the absorbtivty reflectivity product at zero thickness equals 0.95. This relation can be obtained from the previous table: :

$$\alpha_{cw} = 0.95 - 4.1.t \qquad (14)$$

The   heat transfer coefficient from the water surface to the glass cover $(h_t\;)$ is calculated from the following equation [7]

$$h_1 = h_c + h_r + h_e \qquad (15)$$
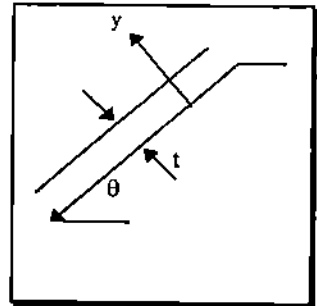
$$h_c = 0.8831 \left[\left(T_w - T_g \right) + \left(\frac{P_w - P_g}{0.265 - P_w} \right) \left(T_w + 273 \right) \right]^{\frac{1}{3}} \qquad (16)$$

$$h_e = 0.0061 \left[\left(T_w - T_g \right) + \left(\frac{P_w - P_g}{0.265 - P_w} \right) \left(T_w + 273 \right) \right]^{\frac{1}{3}} \frac{\left(P_w - P_g \right) L}{T_w - T_g} \qquad (17)$$

$$h_r = \sigma F_{wg} \left[\left(T_w + 273 \right)^4 - \left(T_g + 273 \right)^4 \right] \qquad (18)$$

where
h_c is convection heat transfer coefficient, (W/m^2 C), h_e is evaporation heat transfer coefficient, (W/m^2 C) and h_r is radiaitve heat transfer coefficient, (W/m^2 C)..

The heat transfer from glass cover to cooling water is calculated from this relation [8]:

$$Nu = 0.664 R_e^{0.5} P_r^{0.33} \qquad (19)$$

The heat transfer from colling water to ambient air is calculated from this relation[7]:

$$Nu = c \left(Gr . Pr \right)^n \qquad (20)$$

The value of c and n depend on the value of Gr.
1- for Gr.< 10^3 ,   c=1 ,   n=0,
2- for 10^3 < Gr. < 3.2x 10^5,   c=0.21, . n=1/4,
3- for 3.2x 10^5 < Gr. <10^7,   c=0.075, . n=1/3,
The productivity can be calculated from this equation:

$$D = \frac{q_e}{L} = \frac{h_e \left(T_w - T_g \right)}{L} \qquad (21)$$

Solution of the theoretical model:

The cold water temperature, glass temperature, still water temperature and solar radiation they change all with time. The finite difference numerical method has been used for their calculation. In this calculation, the time interval (Δt) has been taken as 0.5 hour. A smaller interval results as found to be very close, and the calculation time increases. The heat transfer coefficient is calculated using the initial values of temperatures (T_{cwi} =   Tg   = 20 C and T_w=20.01 C), calculate the new values of temperature from the model and then calculate the new heat transfer coefficient. For each time interval the amount of water in the basin is considered as the initial amount of fed water. This is due to recycling of the cooling water which is fed back into the supply of the solar still.

Experimental set up

Two s. gle basin solar stills were constructed in this work. The two solar stills have the same main dimensions and construction. One of this stills is conceived in such a manner to allow the flow of thin layer of water on the upper glass surface. The flow is then recycled and fed into the basin inlet. The basin area of each still is 0.5 x 1 m, the heights of the front and back walls are 0.24 m and 0.5 m respectively. The glass cover slope was 15. The water thickness in the two stills is 0.03 m. A rectangular 4 mm thick glass sheet was fitted in an iron farm. A rubber gasket was used as seal between the glass cover and frame to avoid vapor leakage..

The cooling water flow rate over the glass cover was kept uniform and constant with the help of a regulator and a constant head tank elevated 0.35 m above

the level of still. The dimensions of the tank are 0.63x0.63 m and 0.72 height. The evaporated water in contact with the glass cover condenses and runs down, the condensate is collected at the cover. An inclined rectangular channel was welded at the short side wall of each still from inside surface to collect the condensate. The two stills were insulated from the two sides and bottom by using a wood powder with a thickness 0.05 m. A wooden box was used to contain the still and insulation. The glass cover temperature, water temperature, cooling water inlet and exit temperatures and ambient air temperature, also the solar radiation intensity are measured for the two stills. The stills and all system were manufactured in the Faculty of Engineering, Tanta University, Egypt..
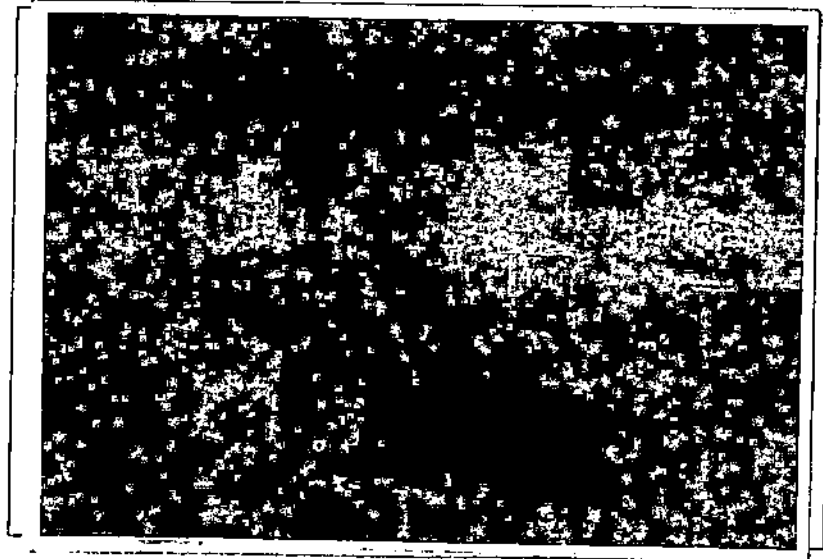
Fig. (2): Photograph of the system used

Results and Discussion

The theoretical results and experimental results were presented together through figures (3) to (16). The figures (3-10) show the variation of glass cover temperature, cooling water temperature, brine water temperature during the day (local time) without glass cover cooling and with glass cover cooling, at different amount of cooling water passing over the glass cover. The amount of cooling water was changed from 0 (no glass cover cooling) to 0.12 Kg/s. It can be seen that the glass temperature and cooling water temperature decrease with the increase of the amount of cooling water flow rate, also the brine temperature decreases with increasing the cooling water flow rate.. It can be observed that the temperature difference between the brine temperature and glass temperature increases with increasing the amount of flow rate of cooling water. The following table shows this difference at different amount of cooling water at noon. For the case of comparison, the experimental results are presented in figures 3,5,6 There are some overestimation of about 9% for the water temperature and glass temperature. This deviation is due to the glass cover

and water temperatures are calculated on the basis on the radiation intensity calculated from the theoretical model [10].

cooling water flow rate, Kg/s	0.0	0.005	0.01	0.03	0.06	0.09	0.12
temperature difference, °C	17	21	24	28.6	31	32	33

The table shows that the value of temperature difference due glass cooling reached about 200% of 0.06 Kg/s and then the increasing value is small.. Also, it can be seen that the temperature difference between the cooling water and the glass cover decreases with increasing the cooling water flow rate.
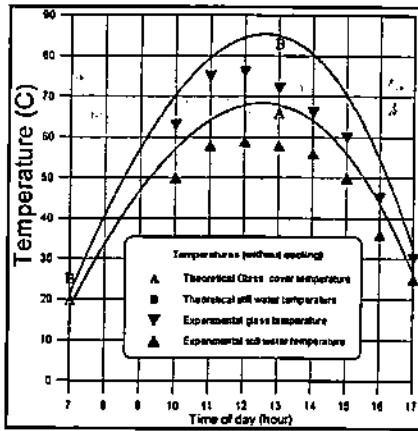
Fig. 3 :Variation of temperature during the day without glass cover cooling
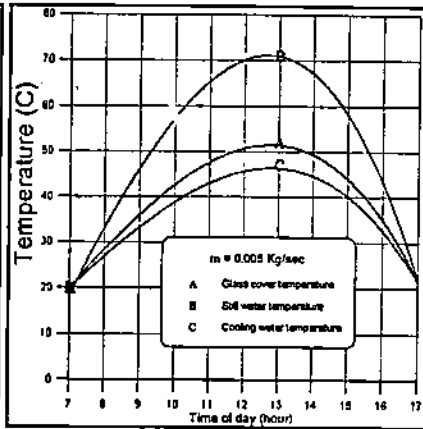
Fig.4 :Variation of temperature during the day at 0.005 kg/sec glass cover water flow rate
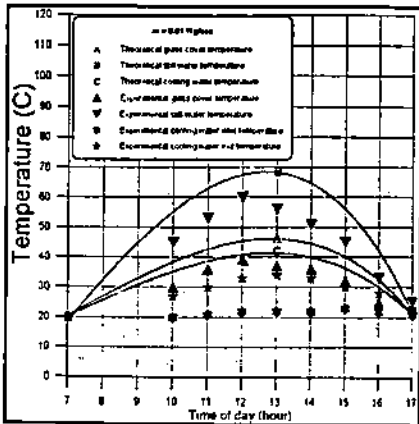
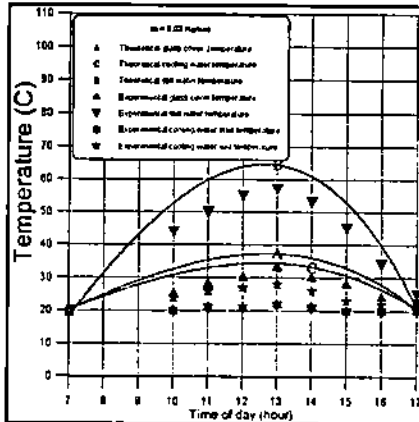Fig.5 :Variation of temperature during the day at 0.01 kg/sec glass cover water flow rate

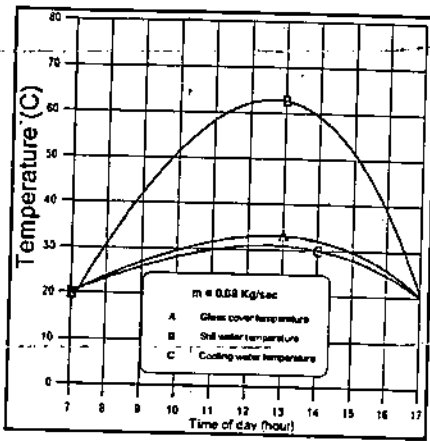Fig. 6 :Variation of temperature during the day at 0.03 kg/sec glass cover water flow rate

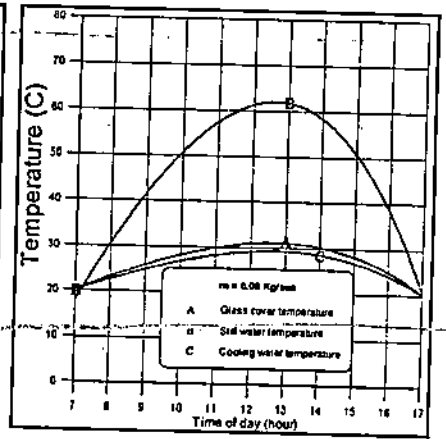Fig.7 : Variation of temperature during the day at 0.06 kg/sec glass cover water flow rate

Fig. 8: Variation of temperature during the day at 0.09 kg/sec glass cover water flow rate

Figure.10 shows the variation of the productivity during the day at different amount of cooling water. It can be observed that the maximum productivity without glass cover cooling reached to 0.38 Kg/m^2.hr. The productivity increases with increase of the amount of cold water, at 0.005 Kg/s reached to 0.53, at 0.01 Kg/s reached to 0.55 and at 1.2 Kg/s reached to 0.59. The increasing value due to the glass cover cooling reached to about 56 %.
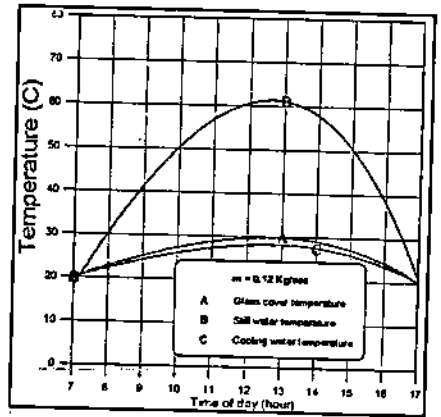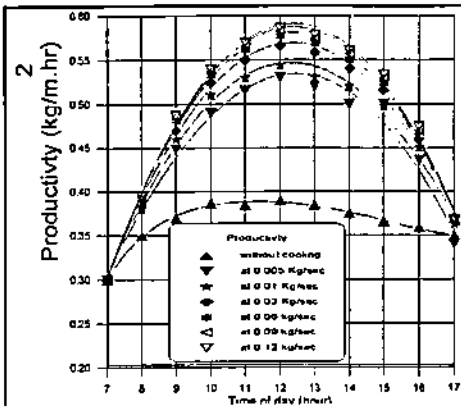
Figure 11 shows the average total solar radiation intensity over the four months   March to June   during the experimental test were performed. This values of the radiation was used in the calculations of the experimental results.

Fig. 9: Variation of temperature during the day at 0.12 kg/sec glass cover water flow rate

Figures 12,13 and 14 show the variation of temperatures at different solar radiation (300, 600, 900 W / m^2) for different flow rates of cold water. It can be seen from the figures that the variation of the temperatures depend on the values of the amount of flow rate and solar radiation , as an example at the higher value of flow rate 0.2 kg/sec the temperature difference is 13 C at solar radiation equals 300 w/m^2, and the temperature difference   at solar radiation 600 W/ m^2 and 900 W/ m^2 is the same value   and equal   35 C". At cooling flow rate equals 0.04/ kg/ sec, the temperature difference is 12 C   at solar radiation equal 300 W/ m^2 and equals 21 C at 600 W/m^2 and equals 30 C at 900 W/m^2 .

Figure 15 shows the variation of productivity with the amount of cooling water at different values of solar radiation. It can be seen from the figure that the productivity increases with the increase the cooling water flow rate until 0.12 kg/ sec and then the increase is small.

Figure 16 shows the theoretical and experimental results for the different cases without glass cooling, at cooling water flow rate 0.01 kg/s and flow rate 0.03 kg/s.

Fig. 10: Variation of productivity during the day at different glass cover cooling water t.ow rates

It can be seen that there are some difference between the experimental and theoretical results. This discrepancy could be explained by some experimental errors such as some distilled water drops falling back into the basin still or the difference is due to the effect of leakage occurs.. The figures show that the experimental and theoretical productivity of the still at 0.03 kg/sec cooling water is higher value than the 0.01 kg/sec cooling water and higher than the productivity without glass cover cooling. As shown in figure the total daily collected mass of water for the two units are 2200 and 3500 (ml/m^2) with and without cooling, respectively. This means that an increase of the daily productivity of about 60% can be obtained with glass cover cooling.
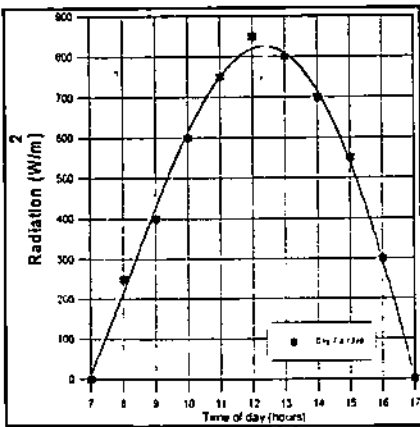

Fig.11 :Variation of solar radiation during the day .
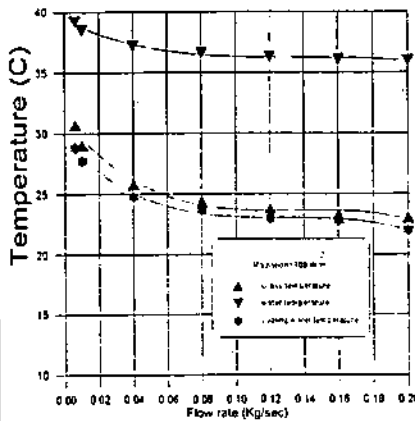

Fig. 12 :Variation of temperature with the flow rates.
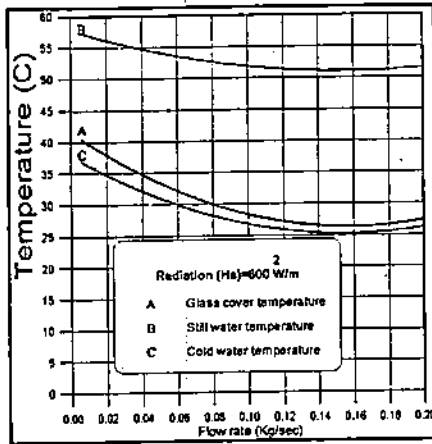
Fig.13:Variation of temperature with the flow rates.
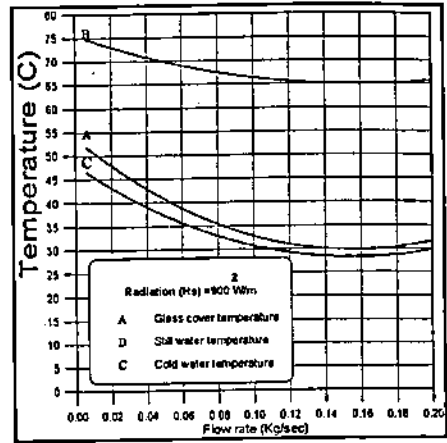

Fig. 14:Variation of temperature with the flow rates.

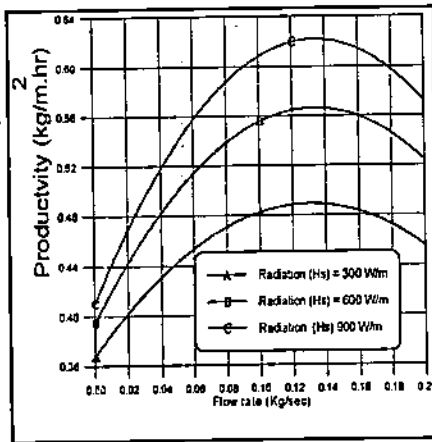

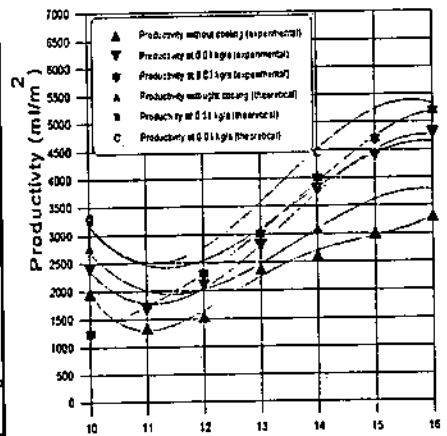Fig.15 :Variation of Productivity with the flow rates at different solar radiation

Fig. 16 :Variation of productivity during the day at the different cooling flow rates

Conclusions:

Based on the present investigation, the following recommendations an conclusions are offered:

1-The presented theoretical model predicts with a reasonable approximation th productivity of solar still.

2- The cover cooling technique has proved to be an adequate and simple tool towar the improvement of solar still productivity. The present experimental resulted sho an increment in productivity reached to about 60%.

Nomenclature

A = still surface area, (m^2)

D = daily output of the still per unit area, (kg/m^{2}hr)

D$_{eq}$= Equivalent diameter (m)

F_{wg} = radiation shape factor from brine surface to inner cover surface (--)

L = latent heat of evaporation, (J/kg)

l = still length, (m)

M_c = heat capacity of cold water per unit area, (J/m^2C)

M_w = heat capacity of water per unit area, (J/m^2C)

Mg = heat capacity of glass cover per unit area, (J/m^2C)

Nu = Nusselt number, (--)

q_e = heat transfer rate in the still by evaporation per unit cover area, (W/m^2)

p_w = partial pressure of water vapor at T_{wn}, (MN/m^2)

p_g = partial pressure of water vapor at T_g, $(MN/m^2$

R_g = glass cover reflectivity

R_{cw} = cooling water reflectivity

R_w = water reflectivity

Ra = Rayleigh number, (--)

T_w = water temperature, (C)

T_{cw} = cooling water temperature, (C)

T_{cwi} = inlet cooling water temperature, (C)

T_{cwo} = outlet cold water temperature, (C)

T_g = glass temperature, (C)

T_b = basin linear temperature, (C)

t_1 = insulation thickness, (m)

t_g = transmativity of the glass, (--)

t = time, hr

V = velocity of cooling water,(m/sec).

Gr = Grashof number , (--)

Pr = Prandtl number, (--)

α_w = water absorbtivity, (--)

α_g = glass cover absorbtivity, (--)

α_{cw} = cooling water absorbtivity, (--)

α_b = bottom surface absorbtivity, (--)

β = coefficient of thermal expansion, (k^{-1})

ρ = density of water, (kg/m^3)

σ = Stefen-Boltzman constant, 5.6697×10^{-8}, $(W/m^2 C)$

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