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Brackish water desalination using solar energy

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Abstract - *Sizeable amounts of brackish water resources are found and distributed over vast cross-national regions in the Sahara desert of Northern Africa. These salty waters can be found sometimes as natural spring water on the surface while the underground aquifers, which can be reached at a hundred meters deep, represent in essence a sea of brackish water beneath the searing desert sands and rocks. These regions of the Sahara desert are characterized by very limited or total lack of rainfall which makes these underground aquifers invaluable and at the same time extremely vulnerable since the natural replenishment process is for all practical purposes inexistent. The brackish waters of these aquifers contain high levels of salt which makes them inappropriate for domestic usage and detrimental to plants or other gardening/agricultural activities. However, the abundant sunshine of the desert can be harnessed to operate solar distillation equipments to produce fresh water. This study presents a theoretical analysis of a new solar desalination equipment that is based on the evaporation/condensation process. Performance results as well as a cost evaluation are reported*.

Résumé - *Des quantités considérables d'eaux saumâtres sont distribuées sur une vaste région transnationale du désert du Sahara, au nord de l'Afrique. Ces eaux salées sont parfois retrouvées sous forme de sources naturelles à la surface, tandis que les aquifères souterrains, qui peuvent être atteints à une centaine de mètres de profondeur, constituent une mer d'eau saumâtre sous le sable et les pierres brulants du désert. Ces régions du désert du Sahara sont caractérisées par une pluviométrie limitée ou nulle, ce qui rend ces aquifères inestimables et en même temps extrêmement vulnérables car leur processus de reconstitution naturel est pratiquement inexistant. Les eaux saumâtres de ces aquifères contiennent des concentrations en sels très élevés, ce qui les rend impropres à un usage domestique et nuisibles aux plantes, donc inutilisables pour des activités agricoles ou de jardinage. Cependant, l'ensoleillement élevé du désert peut être exploité dans le but de faire fonctionner des équipements de distillation solaire pour produire de l'eau douce. Cette étude est une analyse théorique d'un nouvel équipement de dessalement solaire qui est basé sur un procédé d'évaporation/condensation. Les résultats des performances, ainsi que les évaluations des coûts sont présentés.*

Keywords: Brackish water – Desalination - Energy storage - Solar distillation - Solar desalination - Solar heat storage.

1. INTRODUCTION

Population growth in conjunction with technical development have created an imbalance in the supply and demand requirements for fresh water for household and irrigation use on an ever increasing transnational scale especially in remote regions. Of particular interest to many nations is obviously the production of fresh water from underground brackish water aquifers that span vast areas of the arid Sahara and other deserts covering hundreds of thousands of square kilometers. The social, economical and environmental impacts of developing and building solar desalination facilities tailored in size and technical design to these remote, arid and sparsely populated lands

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could be phenomenal. There are desert towns built around these water points that are thriving even on using water with various levels of salt contents. Providing these populations with fresh water is a extraordinary game changer that will bring about a dramatic reversal of the landscape from desolate, harsh and arid to green and hospitable as evidenced by the large scale commercial farming that produce large volumes of high quality fruits and vegetables currently being supplied out of commercial farms from various areas of the Sahara desert such as Adrar, Biskra, El-Oued and others Ouargla, Tamanrasset to name a few.

Solar desalination by way of distillation using the solar greenhouse effect was used successfully a couple centuries ago to produce fresh water from ocean water. The average daily production per square meter of one of those distillation units at that time was about three liters. Nowadays, there are pilot as well as commercial scale plants for the desalination of water using solar energy. These types of installations involve advanced processes and complex technologies that require a high capital investment in equipments, technology as well as skilled manpower. Economic competitiveness of these new technologies' vis-a-vis other processes such as reverse osmosis are yet to be confirmed.

For small scale installations the technical constraints and the economic variables are different. A lot of creative work and many different innovative ideas in the published literature [1-7] were devoted to developing new solar desalination systems with increased output, that is, liters per square meter per day. Solar heat storage using various devices [8-11] proved to be one of many effective ways to significantly improve output. This development work explores the technical capabilities as well as the financial viability of a new and entirely solar distillation equipment that is economically and technically tailored for the desalination of brackish water in arid environment

2. CONTENT

2.1 Experimental

A picture of the solar desalination model used for this study is presented in figure 1. The design features of the experimental model are shown schematically in figure 2.

Fig. 1: Picture of the experimental model

The footprint size of the distillation model is 1170 mm by 910 mm which looks like an elongated rectangle as shown in the picture, figure 1. The walls of the evaporator are made of 2 mm thick galvanized steel sheet for rust protection. The volumetric capacity of the evaporator is 100 liters maximum. The glass cover is a 5 mm thick heat treated glass pane mounted at an inclination angle of 13° with respect to the horizontal plane.

The inclination angle was fixed at 13° to minimize the overall size of the distillation unit and at the same time ensure a set up orientation maximized for the summer sunshine conditions. Observations from previous works revealed that maximum distilled water outputs occur during the month of July, whilst the winter season is characterized by mostly cloudy days that result in equipment occasionally dropping to zero. For regions in the Sahara desert, that is regions that are further south with respect to the location where this study was conducted, the inclination angle of the distillation unit needs to be adjusted in accordance with the latitude of the location. It is worthwhile to note that for regions located along the tropics for example, the glass inclination should not be adjusted to a value lower than 11° in that small inclination angles cause hindrance to the free flow of the condensed droplets of distilled water on the inner surface of the glass pane. Experimental measurements from previous studies [9] showed that at an inclination angle of 9° all the water drops that condensed on the glass pane fall back into the evaporator instead of trickling down to the collection channel, thus causing equipment output to fall sharply.

The sidewalls of the evaporator and those of the concrete base slab are thermally insulated using 20 mm thick polystyrene foam board. A heat exchanger made of 14 mm diameter copper serpentine, shown in cross section in figure 2 as ‘heater tubing’, which serves as a booster heater sits at 10 mm on top of the bottom surface of the evaporator. A similar heat exchanger is embedded inside the concrete slab base of the evaporator which functions as a heat storage device. Two solar heat collectors are connected in separate closed loop configuration to the heat exchanger serpentines of the evaporator and the concrete slab.

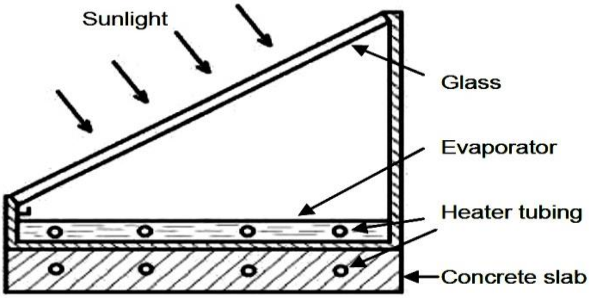

Fig. 2: The experimental model

2.2 Results and discussion

The experimental prototype of this study was developed with the aim of improving the daily output of concrete type greenhouse effect desalination equipments. Performance evaluation of this model was carried out side by side with other standard greenhouse stills for output comparison purposes.

2.2.1 Temperature profile

Temperatures at pertinent locations were measured with type K thermocouples. The readings were recorded automatically using a data logger. Figure 3 shows an example of temperature profile for the day of July 1st, 2015 from 9:00 am to midnight, shown as 24 in figure 3, followed by data for the next day from that point in time to 10:00 am shown as 10 in the graph. Early in the morning before sunrise, the temperature of the glazing was lower than that of water in the evaporator. Between 5:00 and 6:00 am, the temperature of the glass increased faster than that of the evaporator to the point of exceeding it.

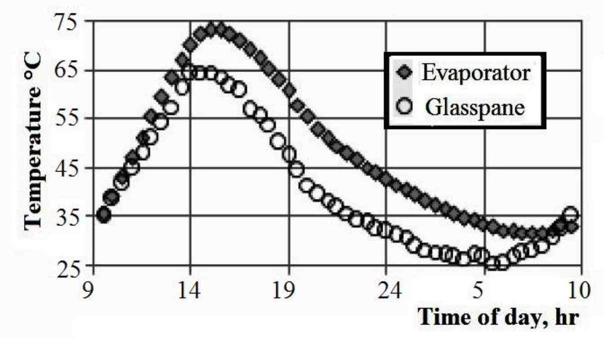

Fig. 3: Example of temperature profile

Between 8:00 and 9:00 am, temperature trends were reversed with the evaporator temperature increasing faster than that of the glazing causing a positive temperature differential between the evaporator and the glass pane favorable to the evaporation-condensation phenomena. The glass pane reaches its maximum temperature of 65°C right after 2:00 pm, while that of evaporator reaches the maximum value of 73°C one hour later at 3:00 pm. During the afternoon cool off and into the night, a natural equilibrium temperature differential ΔT of 10°C settled between the glass pane and evaporator.

2.2.2 Performance of heat storage system

The heat storage feature of the equipment is a noteworthy performance improvement device for the desalination equipment. In desert environments such as the Sahara, the simmering heat on hand can be harnessed and put into valuable use such as heating the concrete base of the desalination unit. As a result, the stored heat in the concrete is released automatically when needed to keep the equipment running when the sun starts going down into sunset and at night. As evidenced by experimental data, figure 4 revealed that 2/3 of the equipment output were collected during daytime from 7:00 am to 7:00 pm while the remaining 1/3 of the total output, was produced during the night from 7:00 pm to 7:00 am of the next morning.

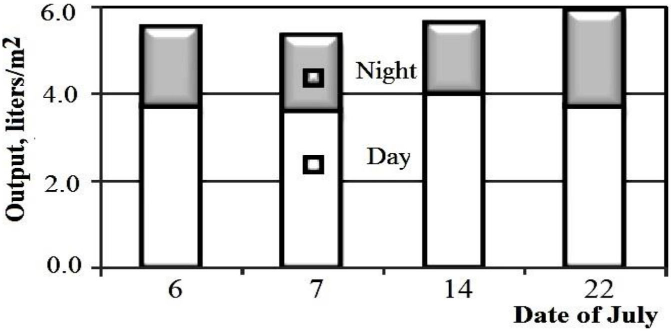

Fig. 4: Effect of Heat Storage

The benefits of heat storage to improve output become more palpable when considering the fact that the amount of direct solar energy input into the equipment after 7:00 pm is negligible. Heat stored in the concrete slab of the evaporator is the only source of energy that drives the process from that point in time and going forward into the night and next morning.

2.2.3 Effects of ancillary solar heaters

The role of the solar heaters in this study is to provide additional heating capacity to the evaporator as well as heat up the concrete slab that serves as an energy storage device. From a performance standpoint, the integration of solar heaters into the prototype design was found to significantly improve equipment output as evidenced by experimental data presented in figure 5. The 'Std' abbreviation in the figure caption, the gray bars, stands for a standard greenhouse effect still with a concrete base but not equipped with any type of additional solar heaters. The black bars, indentified in the figure caption as 'GEH' represent the output of this model when using the 'Greenhouse Effect Heating' only with the solar heat collectors shaded from the sun and disconnected from the equipment. The white bars in the graph correspond to the output of this model with all its solar heating fixtures running.

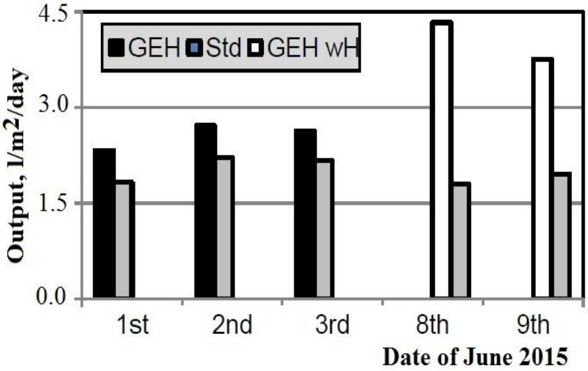

Fig. 5: Effect of auxiliary solar heating

There are three findings that need to be pointed out: First, comparison of the June 1st, 2nd and 3rd data indicated that the output of this model is 20 % higher than the standard greenhouse effect concrete machine due to the design enhancements of this model. Second, the June 8th and 9th data showed the output this model running with all its heating systems under normal conditions was double that of the standard greenhouse effect concrete prototype. The third point is that this study revealed a synergy between the heating systems, namely; the greenhouse effect heating and the additional heating provided by the solar heaters to the evaporator and the concrete heat storage base. The effect on output of all the heating devices acting collectively was higher the sum of their individual contributions.

Measurements performed on days with similar weather conditions showed that, as an example, the output of the equipment was 2790 ml when the equipment was heated by the greenhouse effect only. When the equipment was heated with the solar heat collectors only, i.e. the glazing was shaded, the output was 830 ml. Conversely, when the equipment was operated under its normal conditions with all heaters collectively at work, the output was 4360 ml.

2.2.4 Process kinetics overview

Equipment output of solar distillation devices, such as this model, is a temperature dependent function that follows the Arrhenius exponential equation of the general form,

$$X = X_0 \exp(-\Delta E / R T)$$

Where, X, is the temperature dependent rate function which in this case is the equipment rate of output, X_0, is an experimentally determined rate constant, ΔE, is an activation energy term which is also evaluated experimentally, R, is the ideal gas constant, T, is the absolute temperature in K.

For ease of interpretation, equipment performance evaluation results are plotted as natural log of output rate as a function of reciprocal absolute temperature, that is, $\ln(X)$ as a function of $(1/T)$. Figure 6 shows an example of the so-called Arrhenius plots obtained from output rate measurements collected on July 22nd, 27th, 28th and 29th of 2015 from 7:00 am to 7:00 pm.

Independently of weather conditions, all the data points fall on the same master curve whose shape is a straight line for ideal cases of isothermal conditions of the glass pane condensation surface. Under real life outdoor use conditions, the temperature of the glass panel increases as the sun rises, sometimes reaching temperatures as high as 65°C as reported for example in figure 3. The temperature increase of the glass, unfavorable for condensation, causes the output master curve to bend to lower throughput rates and as a result a reduction of the overall daily output of the equipment as depicted in figure 6.

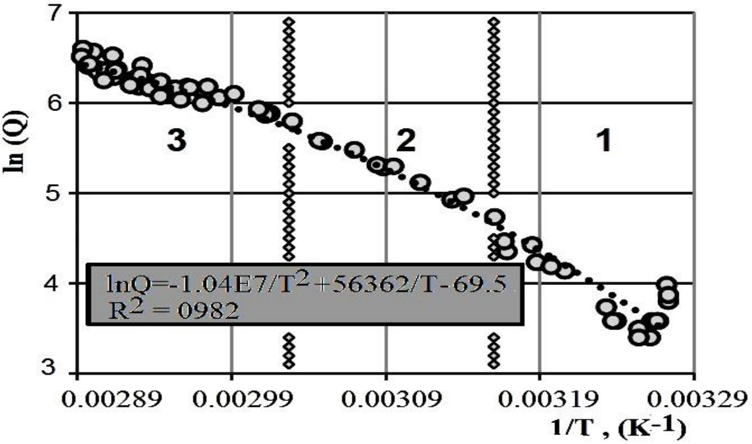

Fig. 6: Non-linear Arrhenius plot

The graph in figure 6 is divided into three zones labeled as 1, 2 and 3. Each of these zones corresponds to a temperature increase, ΔT, of 10 °C. The portion of the graph identified as zone **1** corresponds to the time interval of 7:00 to 11:00 am during which time the temperature of the glass increased by 10 °C causing no appreciable deviation of the master curve from linearity. When the temperature increase of the glass pane exceeds 10 °C, hindrance imposed on the condensation process results in output rate decline as evidenced by the bending of the master curve towards lower throughput rates, represented in figure 6 as zone **2**.

The data points located in zone **3** represent output results from the time interval of 12 noon to 3:30 pm. After 3:30 pm, the equipment enters the cooling off phase. The data points of zone **3** include also the measured equipment output rates for the time period covering 3:30 pm to 7:00 pm. Increase of the glass temperature is detrimental to production. Previous work [9] showed that the rate of condensation decreased exponentially with increasing temperature of the condenser surface in accordance with the Arrhenius model. The net output of the equipment is thus a result of two counter acting exponentials characterizing the evaporation and condensation phenomena.

2.2.5 Mathematical modeling

When isothermal conditions of the glass pane prevail, operation of the distillation unit follows the simple Arrhenius exponential model, $X = X_0 \exp(-\Delta E / RT)$, mathematical treatment of this case is fairly simple in that plots of $\log(\text{output})$ versus $(1/T)$ yield a straight line.

However, when the temperature variation, ΔT, of the condensation surface exceeds 10°C, such as for example from sunrise to noon time, plots representing $\ln(X)$ as a function of the reciprocal absolute temperature $(1/T)$ are no longer linear. For the case being studied, ΔT for the glass pane reached 30°C and even higher, causing a significant bending of the $\ln(\text{output})$ versus $(1/T)$ relationship to lower throughput rates when the sun is at its highest elevation during the day as depicted in figure 6.

The deviation from isothermal conditions of the glass pane is a major drawback of greenhouse effect solar distillation machines, in that the substantial temperature increase of the glass pane causes a sizeable loss of output. From a mathematical standpoint, the daily output of the equipment can be calculated by integrating numerically the temperature profile of the evaporator in that as a general rule, evaporator temperature is the critical variable that drives all these types of processes that operate via evaporation-condensation phenomena. The procedure consists of using the kinetics raw experimental data to derive an empirical constitutive equation as summarized in figure 7.

The numerical integration consists of using the constitutive equation to calculate a ΔQ each value of all individual T's of the evaporator temperature profile, such as the one shown in figure 3, for a time interval of 195 sec which corresponds to the time interval between successive temperature scans. The raw, first pass results of this exercise are summarized in figure 7. The good agreement between the experimental data and the calculated values is a demonstration that the simple classical rate/temperature kinetics model can be utilized to handle a fairly complex process and to predict output of these types of equipments with an acceptable engineering accuracy.

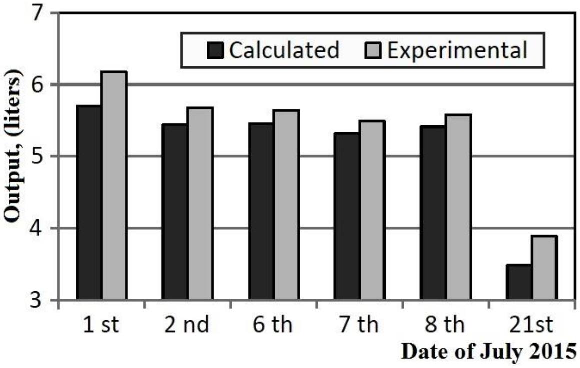

Fig. 7: Comparison of calculated versus experimental output

2.2.6. Financial evaluation

The cost of the equipment was estimated to be 71400 Algerian Dinars (DA). From daily measurements the total yearly output of the equipment was estimated at 740 liters, based on the results that spring, summer and fall average outputs are 200, 440, 100 liters respectively, while winter production was taken as zero to be on the conservative side. Assuming an amortization period of 5 years, the cost of distilled water produced with this solar equipment is 19 DA per liter compared to a similar quality product offered at a retail price of 45 DA per liter. The take away from this simple evaluation is that although the average daily outputs of these types of solar desalination devices are still limited and need improvement to overcome this significant drawback, their economics on the other hand are viable and their impact on the environment can only be positive, hopefully.

3. CONCLUSION

The output of greenhouse solar desalination devices can be improved by providing ancillary heating systems as well as heat storage options. This work revealed that synergy between these heating devices produced a significant performance boost. The energy storage component which maintained the equipment in production at night, contributed 1/3 of the total daily output. Daytime production, that is from 7:00 am to 7:00 pm, accounted for 2/3 of the total equipment output. Because this equipment relies solely on sunshine, output in a cloudy day can go to zero. Consequently, average daily output is highest for the sunniest and longest days of the year that is in the summer. Conversely, output is lowest for the winter season.

Measurements of output rate versus temperature revealed that the solar distillation process follows the Arrhenius exponential model. Non-isothermal conditions of the glass panel caused the performance master curve to deviate from linearity and bending into lowers throughput rates. In fact heat up of the glass pane is a major drawback of greenhouse effect desalination devices. Furthermore, this study showed also that the classical rate/temperature kinetics model, the so-called Arrhenius model, can be used effectively to predict output of solar distillation devices that are driven by evaporation/condensation phenomena. Production cost of distilled water using this equipment is 19 DA per liter compared to 45 DA per liter sales price for similar quality distilled water on the local market. On a final note, this technology is economically competitive and well suited for small scale desalination of brackish water for remote desert areas with plenty of sunshine and readily available brackish water resources. These machines are inexpensive, do not require skilled manpower and do not harm the nature of the Sahara desert magical environment.

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