The Utilization of Solar Energy in a Multiple-Effect Desalinization System*

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ABSTRACT

The University of Arizona has developed a sea water desalinization system which can economically utilize low temperature solar energy. The system consists of a horizontal plastic-covered solar collector, a packed-tower evaporator, and a finned-tube surface condenser. Incoming sea water is preheated in the surface condenser and then pumped to the solar collector where it is heated 5 to 10C. The heated sea water is pumped from the collector to the packed-tower evaporator, where a small fraction is evaporated into a circulating air stream and condensed as distilled water in the finned-tube surface condenser.

To evaluate the system a pilot plant has been constructed in cooperation with the University of Sonora at Puerto Peñasco on the Gulf of California. This plant is designed to produce between 2500 and 5000 gallons of fresh water daily.

The energy for evaporation in the system is derived from ocean water heated in the solar collector during the day. In order to allow design optimization for the entire plant the temperatures in the collector must be accurately predicted. It is shown that this can be done by a simple manipulation of the energy balance equation for the collector.

The resulting theory is applied to a number of cases involving a double glazing collector filled with 2 inches of water. Such a collector will utilize about 24 per cent of the available solar energy if the warm water in the collector in the late afternoon is flushed out and stored for nighttime use in the evaporator.

1. Introduction

In the late fall of 1963 personnel of the Universities of Arizona and Sonora began operating a unique experimental solar desalinization plant at Puerto Peñasco, Sonora, Mexico, near the northern tip of the Gulf of California. This small plant is designed to produce about 5000 gallons of distilled water daily during the summer months. Should it be successful, the plant may be replaced by a larger one yielding several hundred thousand gallons of fresh water daily, enough to meet the needs of a town of 3500 people, at a projected cost of between $0.70 and $1.00 per 1000 gallons. While high by United States standards, the cost is low compared to that in some of the water-starved areas of the world. In summer the people of Puerto Peñasco now pay $15.00 per 1000 gallons for their water. In addition to its high price the water is brackish by U. S. Public Health standards.

Past research has indicated that developing a solar-powered desalinization system to compete with fossil-fueled systems for large-scale applications is a difficult problem, and to date one which has not been solved. The major effort expended using solar energy to solve the problem has been directed toward optimization and lowering of the cost of the conventional single-effect solar still. Such research has led to a clearer understanding of the physical processes involved in such a unit and to lower price for potable water produced by such methods. Unfortunately, projected cost figures[1] for water produced from a conventional still are not, in general, competitive for large-scale application. There are exceptions, of course, and it is possible that in areas of high fossil-fuel cost or for some short-term applications, the conventional solar still might well be the best solution. Nevertheless, it seems certain that if solar energy is to be used for general large-scale desalinization, a method of utilization better than the conventional solar still must be developed.

It has been suggested by some people working in the

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[1] Strobel, J. J., 1961: Developments in solar distillation. United Nations Conf. on New Sources of Energy, Paper No. 35/S/85, 45 pp.

field[2,3] that a system in which the collection of energy, evaporation of brine, and condensation of product water are separated might be a better system for utilizing solar energy than the simple solar still. Such a system could operate multiple-effect, i.e., the energy may be reused in the evaporation process, thus reducing the collector area and possibly reducing the overall cost. However, others in the field have pointed out in detail[4,5] the disadvantages of such a system. Three or four components are necessary instead of one and auxiliary power is required for fluid movement between the components. Hence, the cost could be even greater than that of a conventional still.

Basic energy balance studies (Sellers and Hodges, 1962) indicated that, by using a simple collector and a circulating air stream in a separate evaporator and condenser, it might be possible to develop an economical solar-powered desalinization system for large-scale application.

Early in the investigation it was decided that a simple collector consisting of a shallow layer of water with a clear plastic film on the surface of the water for evaporation suppression would provide the most economical and desirable collector. However, if ambient winds are strong or relatively high operating temperatures are desired, an additional air-supported plastic glazing over the collector is necessary to reduce convective heat losses.

The performance of the solar collector, which is directly dependent on ambient meteorological conditions, must be accurately predicted in order to allow design optimization for the entire system. Therefore, the main purpose of this paper is to derive a simple expression, based on energy conservation considerations, for the temperature of the water flowing out of the collector at any given time. A sample application will be given under conditions typical of Puerto Peñasco in July. First, however, the complete desalinization plant will be described briefly. Further details may be obtained from a series of reports by Hodges *et al.*[2,6,7]

The data and conclusions given in this paper are essentially those of the contractor and are not necessarily endorsed by the Department of the Interior.

2. The solar desalinization plant

The pilot plant at Puerto Peñasco is designed to be an experimental facility. A general flow diagram is shown in Fig. 1. There are three basic components: a solar collector, shown in Fig. 2, in which saline ocean water is heated during the day by the absorption of solar radiation; an evaporator, shown on the left in Fig. 3, in which the ocean water gives off some of its heat and moisture to a stream of cool saturated air; and a condenser, on the right in Fig. 3, in which the now warm saturated air loses some of its moisture (the distillate) and is re-cooled by heat exchange with cool ocean water before reentering the evaporator. The ocean water leaving the condenser is fed into the collector. In addition, there are two 100,000-gallon storage reservoirs, one for the warm ocean water leaving the collector, and another for the ocean water leaving the condenser.

The solar collector, which may have either one or two glazings, covers a total area of 9000 sq ft and consists of five separate units, each 300 ft long. The water depth is approximately 2 inches. During daylight hours water enters and leaves the collector at a rate of 180 gallons per minute. The entering water is derived from the ocean water leaving the condenser which flows continuously into its storage reservoir at a rate of 60 gallons per minute. Over a 24-hour period this provides enough water to operate the collector for only 8 hours. If a longer operating period is desired, as could be the case in summer, the water passing through the collector must be recirculated, either before or after it has gone through the evaporator.

Most of the warm water leaving the collector is stored. Enough is provided in 8 hours to operate the evaporator for a full day. Any excess can either be dumped or recirculated back through the collector, as mentioned above.

The evaporator is a tower, 47 ft in height and 4 to 5 ft in diameter, packed with 2-inch carbon-filled polyethylene Pall Rings, which are designed to provide a maximum wetted surface. The heated ocean water from the solar collector cascades into the top of the evaporator continuously at a rate of 60 gallons per minute. It adds both heat and moisture to a stream of cool saturated air rising from below and then is discharged to the ocean as waste.

The condenser is a tower similar in appearance to the evaporator. The primary condensing surfaces are admiralty lined high-fin aluminum tubes through which cool ocean water passes at a rate of 60 gallons per minute, taking up heat from the now warm saturated air coming from the evaporator. This water heats up

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[2] Hodges, C. N., and A. R. Kassander, Jr., 1962: Distillation of saline water utilizing solar energy in a multiple-effect system consisting of separate collector, evaporator, and condenser. Solar Energy Lab. Intro. Report, Inst. Atmos. Physics, The Univ. of Arizona, 20 pp.

[3] Grune, W. N., R. A. Collins and T. L. Thompson, 1961: Forced convection, multiple-effect solar still for desalting sea and brackish waters. United Nations Conf. on New Sources of Energy, Paper No. 35/S/14, 26 pp.

[4] Löf, G. O. G., 1954: Demineralization of saline water with solar energy. Research and Develop. Progress Report No. 4, Office of Saline Water, U. S. Dept. of the Interior, 80 pp.

[5] Gomella, C., 1961: Use of solar energy for the production of fresh water. United Nations Conf. on New Sources of Energy, Paper No. 35/GR/19(s), 36 pp.

[6] Hodges, C. N., T. L. Thompson and J. E. Groh, 1962: Separate component multiple-effect solar distillation. Solar Energy Lab. Interim Report 1, Inst. Atmos. Physics, The Univ. of Arizona, 48 pp.

[7] Hodges, C. N., T. L. Thompson, J. E. Groh and D. E. Stevenson, 1963: Separate component multiple-effect solar distillation. Solar Energy Lab. Interim Report 2, Inst. Atmos. Physics, The Univ. of Arizona, 49 pp.

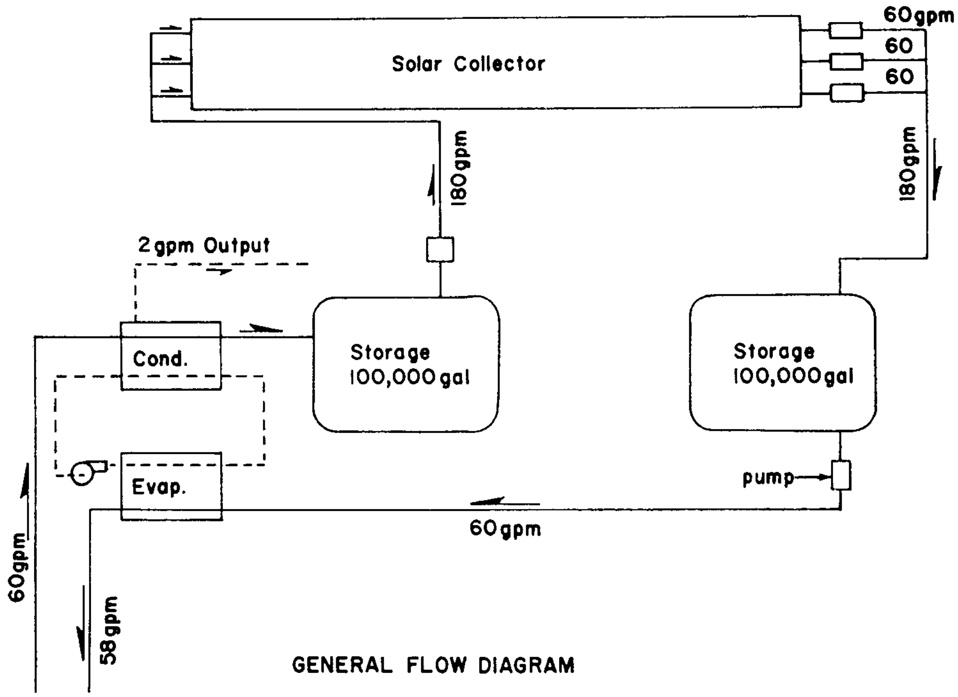

Fig. 1. General flow diagram of the Puerto Peñasco solar desalinization plant.

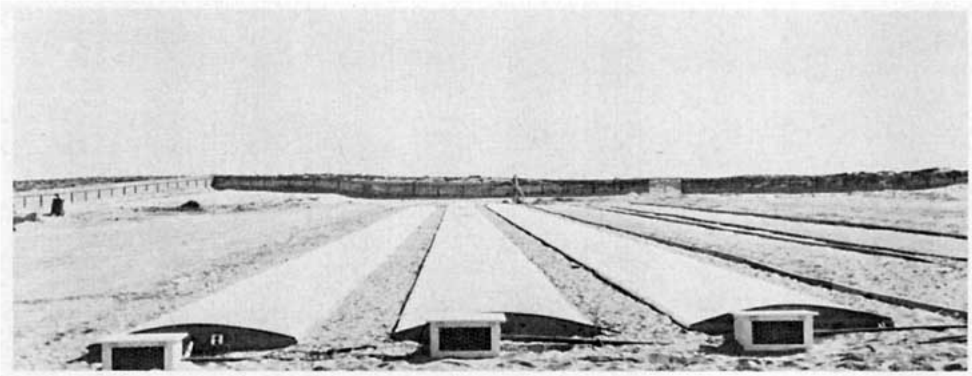

Fig. 2. Three of the five units of the solar collector at Puerto Peñasco. Each unit is 300 ft long and 6 to 8 ft wide. Double glazings of tedlar film are used here. The upper film is air-supported above the lower film, which rests on the water surface.

just about as much as the warm ocean water passing through the evaporator cools off. After it leaves the condenser it is stored for future use in the solar collector.

The saturated air flowing down through the condenser cools and deposits some of its moisture on the aluminum tubes. It then is recirculated to the evaporator where it picks up more heat and moisture from the water from the collector. The condensed moisture passes out of the condenser at a nearly steady rate and is stored.

The evaporator and condenser will be in continuous operation, the energy for evaporation being derived from the warm water collected during the day. For a given collector type and mode of operation, the efficiency of the evaporator and condenser increases and that of the collector decreases as the average temperature of the water leaving the collector increases. It will be shown in the following sections that this temperature can be estimated from energy balance considerations, thus helping to optimize the design of the entire plant.

3. The energy balance of the solar collector

Afternoon wind speeds at Puerto Peñasco average between 10 and 15 mph, making it necessary to use a double glazing solar collector, the upper glazing being air-supported, in order to reduce convective heat losses and to produce relatively high temperature water for the evaporator-condenser system. Hence, only the energy balance of a double glazing collector will be considered here. Actually, this is somewhat easier to handle than a single glazing collector, since the dependence of the large convective heat loss from the latter on the free air wind speed and the air-surface temperature difference is uncertain. For a double glazing collector this loss can be approximated because of its relatively small magnitude.

The development of an expression for the temperature of the water flowing out of a double glazing collector proceeds from the energy balance equation written in the form

$$R = H + G_w + G_s + G_a, \qquad (1)$$

where R is the net radiation, H is the sensible heat flux from the plastic-covered water surface to the air (the convective heat loss), G_w is the sensible heat flux into the water in the collector, G_s is the sensible heat flux into the soil beneath the collector, and G_a is net advection of heat out of the collector in the direction of flow.

The analytic expression used for each term in Eq (1) is discussed below. It will be assumed that the physical state of the collector does not change from one day to the next and that there is no horizontal transfer of heat in the soil normal to the collector. These conditions are equivalent to assuming quasi-steady state and an infinitely wide collector. In addition, it will be assumed that the skies are clear, which is almost always the case at Puerto Peñasco.

a. The net radiation (R). The net radiation is given by

$$R = Q(1-\alpha) - I, \qquad (2)$$

where Q is the incident solar radiation (direct plus diffuse), α is the albedo of the collector surface, and I is the net out-going long-wave radiation. The latter is normally not measured directly and must be estimated from available data. In this study it was obtained from

$$I = \epsilon_s(9.92 - 0.046r) - \epsilon_s\sigma T^4 - \epsilon_g\sigma T^4 + \epsilon\sigma T_w^4, \qquad (3)$$

where ϵ_s is the absorptivity of the double glazing collector surface for long-wave sky radiation, approximated by $\sigma T^4 - (9.92 - 0.046r)$, where r is the relative humidity of the air at 2 m in per cent (see Sellers, 1964); σ is the Stefan-Boltzman constant, T is the air temperature at 2 m, T_w is the instantaneous mean water temperature, and ϵ_g and ϵ are the emissivities of the upper plastic (tedlar) glazing and of the collector surface, respectively. It has been assumed here that the upper glazing is at air temperature. The sum of the first two terms on the right gives the long-wave sky radiation absorbed by the collector surface, allowing for depletion by the upper glazing. The third term represents the long-wave radiation from the upper glazing absorbed by the collector surface, and the last term the long-wave radiation from the collector surface.

Letting

$$T_w = 0.5(T_{w1} + T_{w2}), \qquad (4)$$

FIG. 3. The evaporator (left) and condenser (right) components of the Puerto Peñasco solar desalinization plant. The Gulf of California is in the background.

where T_{w1} and T_{w2} are the mean water temperatures at the beginning and end of a given hour, respectively, noting that

$$\epsilon\sigma(T_w^4 - T^4) \simeq 4\epsilon\sigma T^3(T_w - T),$$

and regrouping terms, gives for Eq (2)

$$R = Q(1-\alpha) + (\epsilon_s + \epsilon_g + 3\epsilon)\sigma T^4 - \epsilon_s(9.92 - 0.046r) - 2\epsilon\sigma T^3(T_{w1} + T_{w2}). \qquad (5)$$

b. The convective heat loss (H). This is given by

$$H = \rho c_p D(T_w - T) = 0.5\rho c_p D(T_{w1} + T_{w2} - 2T), \qquad (6)$$

where ρ is the air density, c_p is the specific heat of air at constant pressure, and D is a heat transfer coefficient, which, in the present case of free convection between the two plastic glazings, may be assumed to be a constant. The value of D appropriate for the type of collector used has been estimated by one of the authors (T. L. Thompson) to be about 800 cm hr^{-1}.

c. The sensible heat flux into the water (G_w). The rate at which energy is stored in the water in the collector is directly related to the rate of change of temperature of the water, $\Delta T_w/\Delta t$ and to the depth of the water, Δz_w. That is,

$$G_w = C_w \frac{\Delta T_w}{\Delta t} \Delta z_w = C_w(T_{w2} - T_{w1})\Delta z_w, \qquad (7)$$

where C_w is the heat capacity of the water and Δt has arbitrarily been set equal to 1 hour.

d. The sensible heat flux into the soil (G_s). It is known from heat flow theory that, with a sinusoidal variation of the surface temperature, equated here with the water temperature, the flux of heat into the soil beneath the collector, should be given by

$$G_s=\left(\frac{\pi}{24}\right)^{\frac{1}{2}} C_s\kappa^{\frac{1}{2}}\left[a\frac{\Delta T_w}{\Delta t}+c(T_w-\bar{T}_w)\right], \tag{8}$$

where C_s and κ are, respectively, the heat capacity and thermal diffusivity of the soil, $\bar{T}_w$ is the 24-hour mean water temperature, and a and c are constants theoretically equal to 3.8 hr and 1.0, respectively. Observations, to be mentioned later, indicate that c is also 1.0 when there is a thin layer of water on the soil surface; however, a is somewhat smaller, of the order of 0.5 hr. With these values and again letting Δt be 1 hour, Eq (8) becomes

$$G_s=\left(\frac{\pi}{24}\right)^{\frac{1}{2}} C_s\kappa^{\frac{1}{2}}(T_{w2}-\bar{T}_w). \tag{9}$$

e. The net advection of heat out of the collector (G_a). This term is proportional to the speed, v_w, at which the water flows through the collector, the temperature difference, T_0-T_i, between the water flowing out of the collector and that flowing in, the water depth, Δz_w, and the length of the collector, Δx_w. Thus,

$$G_a=C_w v_w(T_o-T_i)\frac{\Delta z_w}{\Delta x_w}, \tag{10}$$

where C_w is the heat capacity of the water. The temperature difference T_0-T_i may be related to $T_{w1}+T_{w2}$ by letting

$$T_w=0.5(T_{w1}+T_{w2})=T_i+0.5b(T_0-T_i), \tag{11}$$

where b is a constant equal to 1.0, except when

$$P\leq\frac{5}{9}\frac{\Delta x_w}{v_w}, \tag{12}$$

in which case

$$b=2-\frac{9v_w}{5\Delta x_w}P,$$

where P is the time in hours since either (1) the flow was started or (2) a change was made in the temperature of the water entering the collector. The factor b takes into account the very non-linear temperature variation along the length of the collector during the time interval defined by Eq (12) and, in effect, gives greater weight to T_0 than T_i in estimating T_w by Eq (11) during this period. Introducing Eq (11) into Eq (10) gives

$$G_a=C_w v_w(T_{w1}+T_{w2}-2T_i)\frac{\Delta z_w}{b\Delta x_w}. \tag{13}$$

During the nighttime when there is no flow, $v_w=0$, and this term is absent.

Combining Eq (5), (6), (7), (9), and (13) yields

$$A_1+A_2\bar{T}_w+A_3T_i-A_4T_{w1}=A_5T_{w2}, \tag{14}$$

where

$$A_1=Q(1-\alpha)+(\epsilon_s+\epsilon_g+3\epsilon)\sigma T^4 -\epsilon_s(9.92-0.046r)+\rho c_p DT,$$

$$A_2=\left(\frac{\pi}{24}\right)^{\frac{1}{2}} C_s\kappa^{\frac{1}{2}},$$

$$A_3=2C_w v_w\frac{\Delta z_w}{b\Delta x_w},$$

$$A_4=2\epsilon\sigma T^3+0.5\rho c_p D-C_w\Delta z_w+0.5A_3,$$

$$A_5=2\epsilon\sigma T^3+0.5\rho c_p D+C_w\Delta z_w+0.5A_3+A_2.$$

These coefficients are a bit more complicated if Δt is not 1 hour, but the same general form of the solution, Eq (14), still applies. For an insulated collector $A_2=0$; for a static collector, i.e., one in which there is no water motion, $A_3=0$.

The coefficients are known or can be estimated from available data. All that remains is to determine T_{w2} from Eq (14). This can be done, if T_i, the temperature of the entering water, is known, by assuming values for $\bar{T}_w$, the average 24-hour water temperature, and T_{w1}, the average water temperature at a particular time. Eq (14) is then applied successively hour-by-hour, with provision that T_{w2} at the end of one hour must equal T_{w1} at the start of the next hour. Further, because of the quasi-steady state assumption, the value of T_{w2} computed for the end of the 24th hour must equal the initially assumed value of T_{w1}. If it does not, the latter should be replaced by the former and the calculations continued until equality is reached.

When this process is completed and the values of T_w are computed it will usually be found that their average does not equal the initially selected value of $\bar{T}_w$. Therefore, the calculations must be repeated with a new value for $\bar{T}_w$, preferably the value at the end of the first set of calculations plus one-third of the deviation from the initial guess. Convergence is usually quite rapid, both to T_w and to $\bar{T}_w$, if all coefficients and absolute temperatures are computed to five significant digits.

4. Results

Before applying the theory outlined in the previous section to Puerto Peñasco, it is appropriate to compare temperatures estimated from Eq (14) with actual observations taken at Tucson on 4 July 1963 using a double glazing static collector. This is done in the top part of Fig. 4. The observed temperatures are indicated by the circled points and the estimated temperatures by curve A. The agreement is generally good, partly because the value of the constant *a* in Eq (8) was determined from this particular set of data. Nevertheless, it may still be concluded that the theory, culminating in Eq (14), apparently reproduces the major features of the physical processes involved. The observed data for the first two hours are not considered reliable because the upper glazing was cleaned just before the experiment began and may have been wet during this period.

Climatological data for Puerto Peñasco in July and values of the various collector parameters are given in Table 1. The albedoes listed are those given by Edlin and Willaner[8] increased by about 5 per cent to take into account shading of the water surface by the side walls of the collector and the accumulation of dust on the plastic glazing. The emissivities used were derived from information given by Whillier (1963), assuming a long-wave transmittance of 0.25.[8]

TABLE 1. July climatological data and collector parameters for Puerto Peñasco.

Hour centered on (MST)	Q (cal/cm²/hr)	α	r (per cent)	T (°K)
01			68	300.8
02			68	300.4
03			68	299.9
04			68	299.8
05			65	299.7
06	4.6	0.72	65	299.8
07	21.2	0.47	58	300.7
08	42.2	0.30	52	302.4
09	62.9	0.22	49	303.8
10	78.5	0.19	47	304.6
11	90.5	0.17	46	305.2
12	96.4	0.17	46	305.4
13	94.0	0.17	46	305.5
14	86.4	0.17	46	305.6
15	75.2	0.19	42	306.8
16	55.4	0.22	47	305.7
17	34.6	0.30	48	305.4
18	17.6	0.47	49	304.9
19	4.1	0.72	54	304.3
20			59	303.3
21			64	302.4
22			68	301.9
23			69	301.4
24			69	301.0

$\epsilon = 0.8675$

$\sigma = 487.9\times10^{-11}$ cal/cm²/hr/K⁴

$\rho c_p = 0.2761\times10^{-3}$ cal/cm³/K

$C_w = 1.0$ cal/cm³/K

$C_s\kappa^{\frac{1}{2}} = 1.5$ cal/cm²/hr$^{\frac{1}{2}}$/K

$\epsilon_g = 0.63$

$\epsilon_s = 0.2443$

$\Delta z_w = 5.08$ cm

$\Delta x_w = 9144$ cm

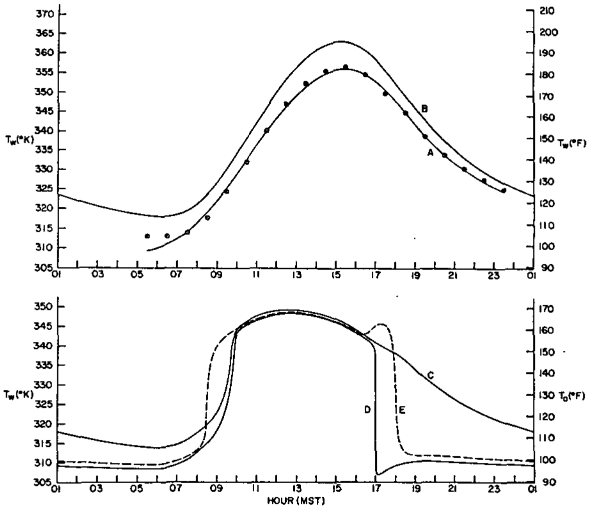

FIG. 4. A: Static collector water temperature data taken on 4 July 1963 at Tucson, Ariz.; the circled points give the observed data, the smooth curve the theoretical estimates. B: Estimated static collector water temperatures for July at Puerto Peñasco. C: Estimated collector water temperatures at Puerto Peñasco in July when warm water at 341K flows through the collector at a speed of 88 m hr⁻¹ from 0830 to 1630 MST; there is no flow from 1630 to 0830 MST. D: Same as C, except from 1630 to 1700 MST when the collector is flushed with cold water at 303K flowing at a speed of 183 m hr⁻¹. E: Same as D, except that the initial flow of warm water is started at 0730 MST and the flushing occurs from 1530 to 1830 MST at a speed of 30.5 m hr⁻¹. During periods when water is flowing through the collector the temperatures given are those of the water leaving the collector; when there is no flow the average temperature of the water in the collector is used.

The estimated variation of the temperature of a 2-cm layer of water in a double glazing static collector at Puerto Peñasco is given by curve B of Fig. 4. This information is presented mainly to show that the water in such a collector will be several degrees warmer than that in a similar collector at Tucson (curve A), even though midafternoon air temperatures at Tucson on 4 July 1963 were more than 5C higher than the average values for Puerto Peñasco. Puerto Peñasco has a greater solar radiation input (by about 7 per cent), higher average air humidities (57 per cent as opposed to 43 per cent at Tucson), and slightly higher nighttime temperatures. By using a smaller depth of water and insulating the collector bottom, it would be possible to raise the temperature to the boiling point in the midafternoon.

A number of different operational procedures were studied. Only three of these will be discussed here. In case I, curve C of Fig. 4, warm water at a temperature

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[8] Edlin, F., and D. E. Willaner, 1961: Plastic films for solar energy applications. U. N. Conf. on New Sources of Energy, Paper No. 35/S/33, 28 pp.

of 340.94K (154F) is circulated through the collector at a constant speed of about 88 m hr^{-1} for 8 hours beginning at 0830 MST. Since the collector is 91.4 meters long, this means that a complete water turnover occurs every 62 minutes. The efficiency of this procedure in utilizing solar energy may be determined by dividing the net amount of energy advected out of the collector during the 8-hour period by the total solar radiation received during the day (764 cal cm^{-2}). Obviously this cannot be negative; otherwise, there would have to be an additional source of energy available to warm the water fed into the collector.

In the present case the efficiency is 0.16, implying that only 16 per cent of the available solar energy is actually collected in the warm water stored for future use in the evaporator-condenser system. A significant portion of the remainder is left in the collector at 1630 MST, to be lost by reradiation during the night. This immediately suggests that higher efficiencies could be achieved by draining off and storing the warm water left in the collector at the end of the day and replacing it with cool water, possibly that discharged from the evaporator.

Case II, then, is identical to case I, except that the collector is flushed from 1630 to 1700 MST with cool 302.60K (85F) water flowing at a speed of about 183 m hr^{-1}. As shown by curve D of Fig. 4, the effect of the flushing is to cause a sharp decrease of more than 30C in the average water temperature between 1630 and 1700 MST. After this time the water first heats slightly until 1930 MST and then cools to a minimum of about 308K(95F) at 0530 MST.

During the period of collector operation (0830 to 1700 MST) water temperatures remain slightly lower than those observed in case I. Nevertheless, the average temperature of the stored water is higher in the present case (345.66) and yields a collector efficiency of 0.24. In case I part of the stored water is the cool water initially in the collector at the start of the operational day; in case II this is replaced by the warm water remaining in the collector at 1630 MST.

Subsequent to the completion of this analysis it was found that it would be too expensive to install a pumping system that would flush the collector in 30 minutes, and so the question arose as to whether using a 3-hour flushing period instead would significantly reduce the collector efficiency. The appropriate calculations were carried out and are presented as curve E in Fig. 4. In this case (case III), the normal flow of warm water through the collector is started at 0730 MST and continued to 1530 MST. The flushing operation is then begun and continued to 1830 MST. During this latter period the slow flow velocity (30.5 m hr^{-1}) gives the water plenty of time to warm up before it leaves the collector. As a result, there is a secondary temperature maximum of the exiting water near 1720 MST. This maximum, however, is still far below that observed with a static collector at the same time (curve B).

The collector efficiency for case III is 0.22, higher than that for case I and slightly lower than that for case II. The result of this analysis is, then, that the slight increase in efficiency from case III to case II does not seem to warrant the expense of installing a pumping system that would flush the collector in 30 minutes. However, considerations of the economics of the whole desalinization system, which are beyond the scope of this paper, may serve to modify this result.

5. Conclusions

The purpose of this paper has been twofold. First, to describe the experimental solar desalinization plant being operated at Puerto Peñasco, Sonora, Mexico, by the University of Arizona and the University of Sonora, and second, to illustrate one practical application of the surface energy balance equation.

The authors are convinced that the desalinization process described is workable and can be benefically used to provide fresh water at a moderate cost in many of the water-starved regions of the earth. The project is still in the research stage and undoubtedly will be for several years to come. There are still many problems to be solved and many improvements to be made. Much of the progress achieved so far has come about only through the close collaboration of engineers and meteorologists. This will continue to be the case even if the solar collector component of the system is eventually replaced as a source of heated water either by the discharge from coastal power plants or by warm brackish ground water pumped from depths 1500 to 2000 ft below the surface, as some have suggested.

Only a few of the collector analyses actually carried out were discussed here. In brief summary, the highest efficiencies, exceeding 0.35, are obtained using double glazing collectors with insulated bottoms. At Puerto Peñasco the convective heat loss to the atmosphere from a double glazing collector is only about one-third of that from a single glazing collector. As a result, the latter is relatively inefficient and in July can produce water at temperatures barely exceeding 330K.

There are numerous other climatological problems for which the surface energy balance equation serves as an excellent point of departure. Penman (1948) and Budyko (1956) have both used this approach to estimate potential evapotranspiration. It could also be used, with only slight modification, to study the effect of albedo on desert surface temperatures and to investigate the complex interrelationship which exists between evapotranspiration, convective heat loss, soil moisture, and wind speed. However, more must be known, in particular, about the appropriate transfer coefficients before the results of such studies can be fully accepted.

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