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A STUDY OF THE EFFICIENCY OF VARIOUS DESIGNS OF SOLAR STILLS FOR PRODUCING POTABLE WATER

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Summary

The design, construction and operation of six different types of solar stills is described. The average production rate of a conventional solar still is found to be 2.50 $l.m^{-2}day^{-1}$ *with an overall efficiency of 28.45 percent. Internal and external mirrors attachments to the still will give 20.32 and 58.20 percent higher production rates respectively. However, decreasing the depth/width ratio of the still from 1:9 to 1:3 will decrease the production rate by 44.22 percent.*

Introduction

In many regions of the world there is a serious shortage of potable water. In tropical developing countries this shortage compounded by malnutrition gives rise to waterborne diseases which afflict a significant percentage of the population. Not only does this health problem cause sickness and disease to the individual, but it also affects the economy of a country through absenteeism of its working force.

The supply of piped water which is suitable for human consumption, to an increasing segment of population, is one major development goal of many countries in Asia. In terms of investment this is costly and in an upcountry rural village a conventional water treatment plant and its associated facilities can become a very expensive proposition. Paradoxically, in many tropical countries there is no shortage of water *per se* – it is only the quality that is lacking. Brackish water from ponds and ditches, and sea water are available – often readily. The problem or the challenge is to convert the water, in whatever form it may be, to a suitable quality. The use of solar stills is one possible technique – with the added advantages of being ecologically clean and the solar energy being a free fuel source.

Solar stills are not new devices or inventions. As long ago as 1883 a very large still has been operated commercially and successfully in northern Chile[1]. However, there has been very little change or modifications to the basic configuration of a

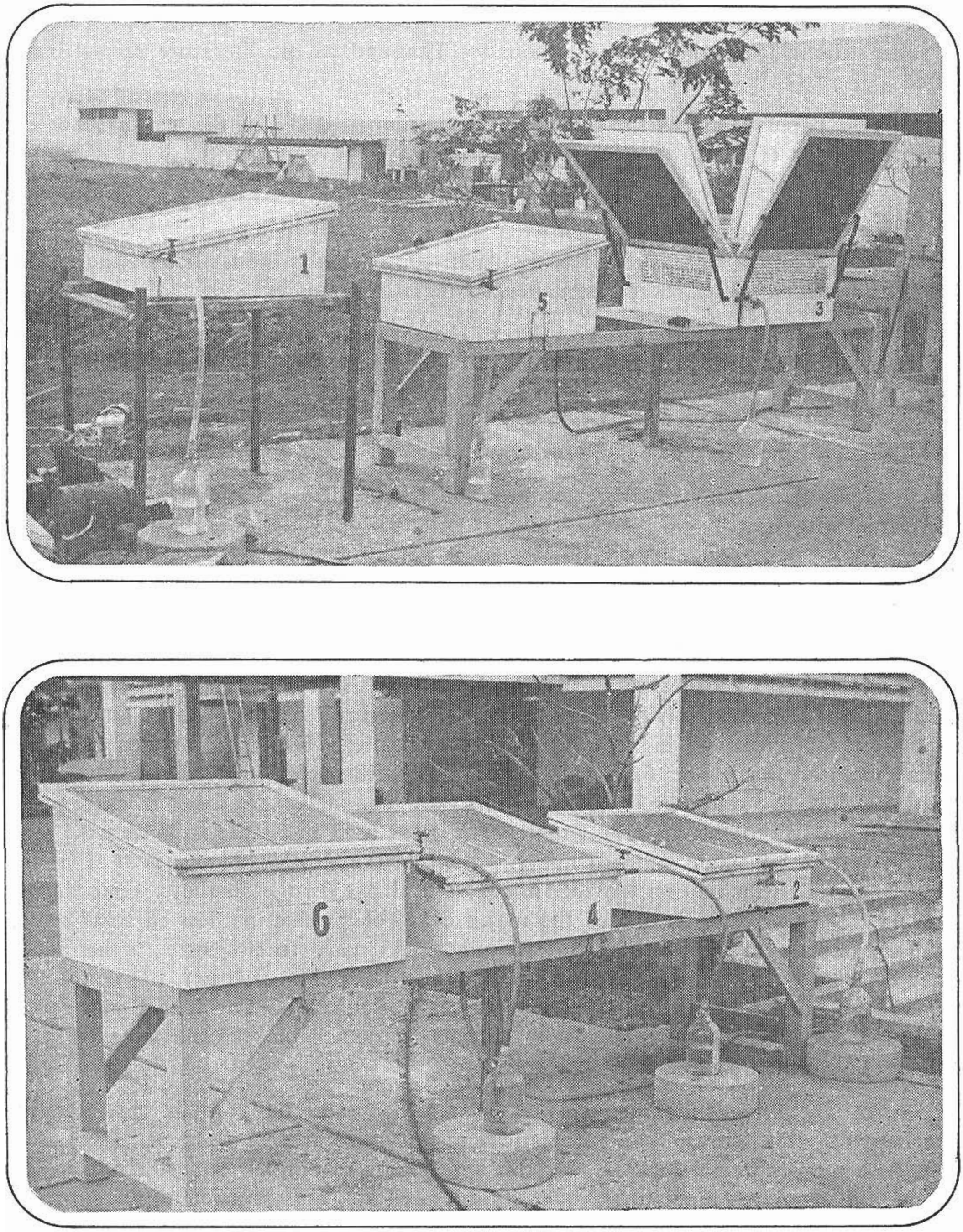


Fig. 1 Views of the Experimental Solar Stills

solar still. Also, there has been only limited published reports on the performance of solar stills in tropical regions but none for Thailand, as the literature review indicated

This paper describes the results of a continuing study of the performance of various designs of solar stills in Thailand.

Method

Six prototype solar stills were designed, constructed and installed at the Asian Institute of Technology for performance characteristic studies[2].

Unit 1, was a conventional solar still as shown in Fig. 1 and served as the reference unit. All the other five units were modifications of the basic unit.

Unit 2, had mirrors fixed on the inner walls of the still.

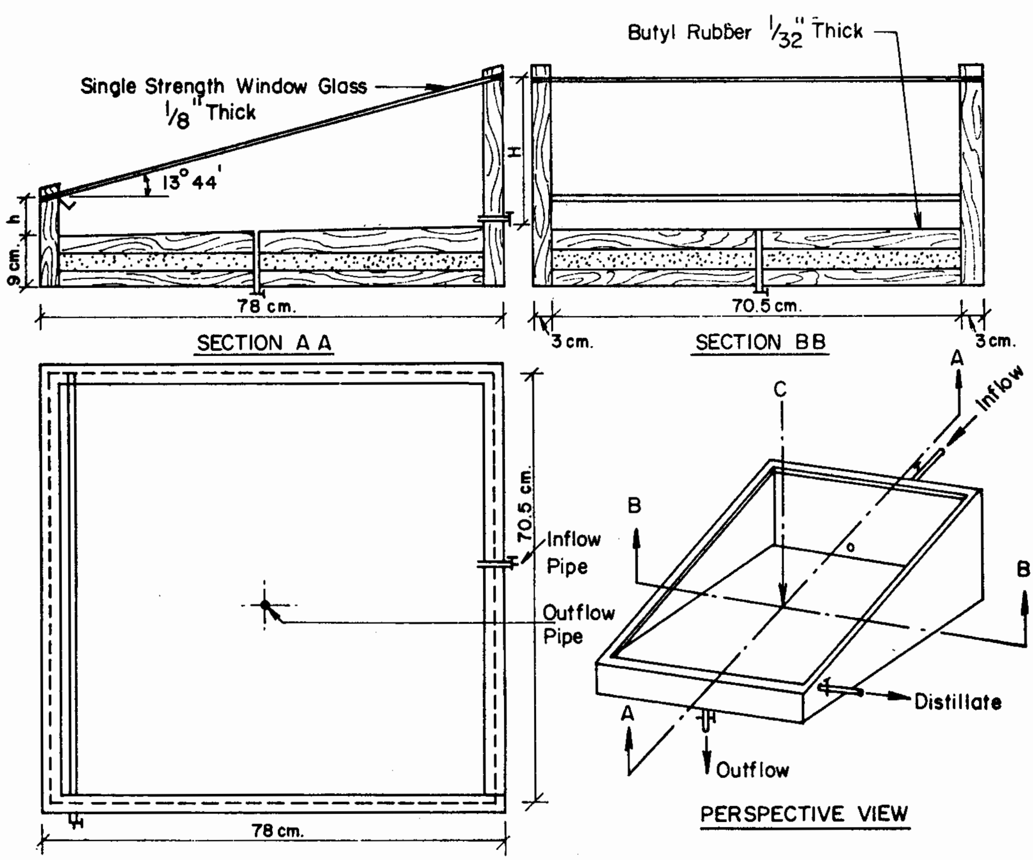
Unit 3, had four adjustable external mirrors.

Units 4, 5 and 6, had greater basin depths of 20%, 40% and 60% respectively, compared with unit 1.

The frames of all the units were made of wood and had surface dimensions of 70.5 cm × 70.5 cm. In order to reduce conductive losses and for economy of construction of the units, the space between the two wooden base plates was filled with saw dust as insulating material. All the units with the exception of unit 3, had a black butyl rubber lining of 1 mm (1/32 in) thick laid over a polyurethane sheet. Unit 3, instead of the rubber lining had a galvanised iron plate painted black, so that it can withstand higher operating temperatures. V-shaped wooden channels were separately made and fixed at a slope to the stills, to permit gravity flow from units 1, 2, 3, 4, 5 and 6. With unit 3, the flow channels were made of galvanized iron and welded to the metallic frame. The glass used in all the stills were 3.5 mm (1/8 in) thick of single strength and the slope of the glass cover was set at an angle of $13^\circ 44'$. This inclination provided adequate drainage for the distillate. In order to prevent leakages, which is one of the major cause of production loss in solar stills, rubber gaskets were inserted between all joints. All glass frames were further insulated externally with adhesive tapes. The distillate channel of each unit was connected to a graduated container by a 1.5 cm diameter flexible tube. Similarly, each unit could be connected to the supply feed tank through a detachable flexible tube. Fig. 2 shows the constuction details of the units.

A bimetallic actinograph was used to record total daily radiations between sunrise and sunset hours and an automatic temperature recorder. Tempscribe was used to record ambient temperatures. In addition, hourly readings were also recorded for inside and outside temperatures, quantity of distillate, and position of the mirrors for unit 3.

Sea feedwater used in the experiments was prepared according to the American Society for Testing Materials Specifications[3].



Unit No.	Height h	Height H	Number	Remarks
Solar Still No. 1,3	8 cm.	25 cm.	2	Unit No. 2 has
" " " 2	8 cm.	25 cm.	1	Plane Mirrors
" " " 4	13 cm.	30 cm.	1	on Inside Walls
" " " 5	18 cm.	35 cm.	1	
" " " 6	23 cm.	40 cm.	1	

Fig. 2 — Construction Details of Solar Stills

Results and Discussion

Solar radiation intensity, ambient temperature and temperatures of solar stills

The mean solar radiation intensity recorded at Rangsit during the study period was 5.7 kW m^{-2} day^{-1} while the mean ambient temperature computed from daily thirteen hour readings was 25.6° C. Typical hourly temperature of glass surface, distiller fluid and ambient temperatures for the units are shown in Fig. 3. Maximum still temperatures were recorded in unit 3 which confirmed the effectiveness of external mirrors. During the initial phase of the investigation, the feedwater temperatures of units 3 and 5 were found to be higher than the glass temperature, thereby preventing condensation. However, this problem was alleviated by drilling small holes in the reflector casing of unit 3 to permit greater air circulation thereby improving condensation. In units 5 and 6, the same problem was experienced and was found to be due to the extra shade caused by the deeper side walls of the units. This was a major factor causing lower production rates in units 5 and 6, and is discussed in greater detail later.

Solar stills production rates and overall efficiencies

The effects of solar radiation intensity on production rates for each of the stills are shown in Fig. 4 and 5. With an average solar radiation intensity of 5.7 kW m^{-2} day^{-1} a conventional still will produce 2.5 $l.m^{-2}$ day^{-1} (Fig. 4). The slope of the lines in the graphs was computed by regression analysis and the coefficients are given in Table I.

TABLE I – COMPUTED PARAMETERS OF SOLAR RADIATION AND PRODUCTION RATE RELATIONSHIP

Water production ($l.m^{-2}$ day^{-1}) = a + b × solar radiation (kW m^{-2} day^{-1})
where, a = intercept
b = regression coefficient

Unit No.	a	b	Standard Deviation	Remarks
1	−2.09976	0.80753	0.35324	Level of confidence is greater than 99% for all unit analysis. Concentration factors for units 2 and 3 are 1.02 and 2.00 respectively as given by Cooper[4] and Brinkworth[5]
2	−0.61978	0.63652	0.36031	
3	−4.72250	0.76269	0.70648	
4	−0.05365	0.43689	0.35324	
5	−0.8988	0.53222	0.35324	
6	−1.20564	0.45602	0.35324	

Typical overall efficiencies of the stills are plotted and shown in Fig. 6 and the minimum, maximum and average production rates during the study period for all units are given in Table II.

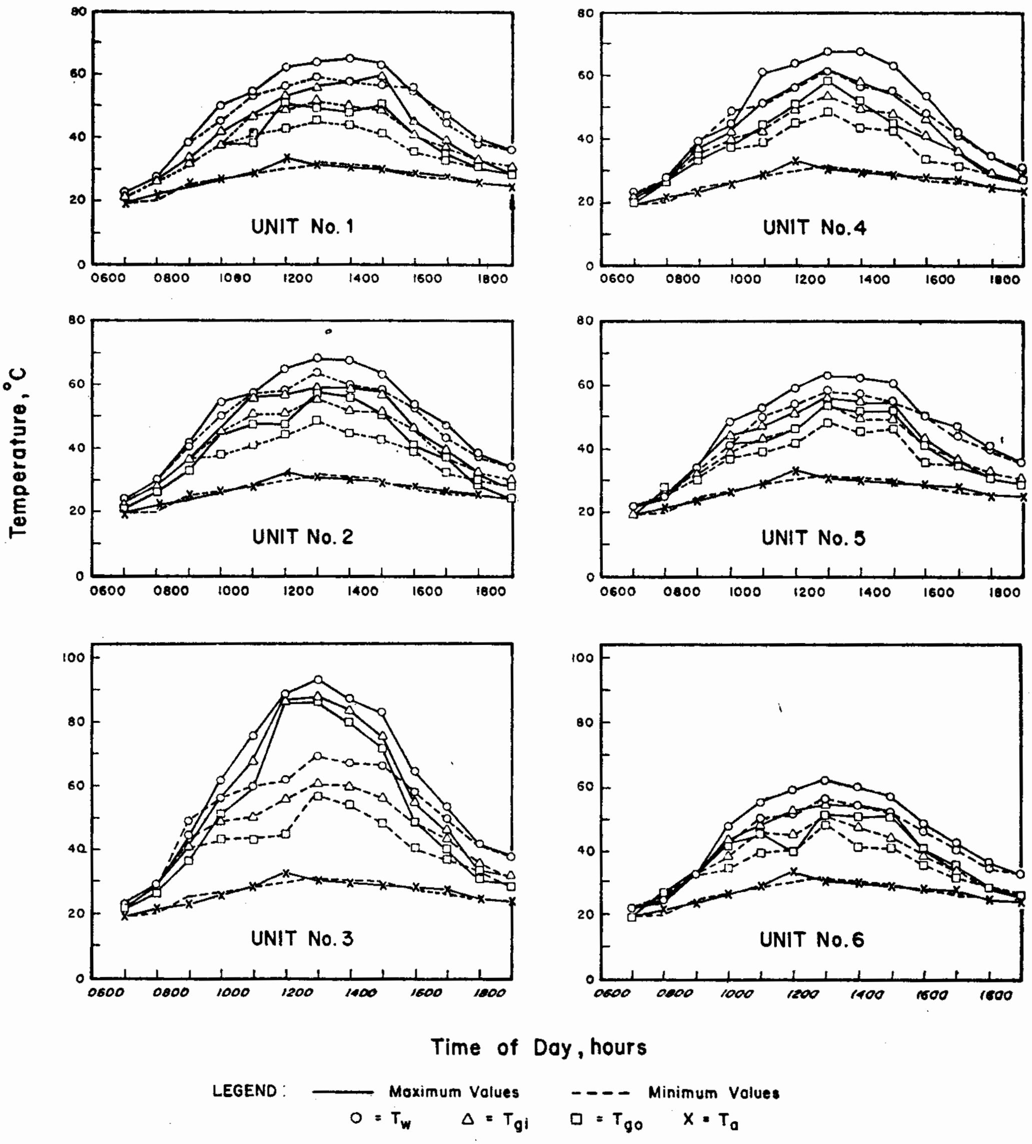


Fig. 3 Typical Variations of Temperatures of Solar Stills with Time.

TABLE II – PRODUCTION RATES AND AVERAGE EFFICIENCIES OF SOLAR STILLS

Unit No.	Production rate, ($l.m^{-2}$ day^{-1})			Actual average overall efficiency, (Percent)
	Maximum	Maximum	Average	
1	1.74	2.86	2.51	28.45
2	2.46	3.35	3.02	34.23
3	2.64	4.95	3.97	45.00
4	2.02	2.70	2.37	26.86
5	1.68	2.32	2.17	24.59
6	0.94	1.52	1.40	15.87

The efficiency of a solar still depends upon the following factors:

i) Unproductive conductive heat losses to the surroundings from the sides and base.
ii) Combined convection, evaporation and radiation to the inside glass surface.
iii) Vapour leakage.
iv) Brine leakage from the basin.
v) Sensible heat of condensate.

The actual average overall efficiency N_A, of each unit was calculated to be:

$$N_A = \frac{\text{Still output} \times \text{Heat of condensation of water vapour}}{\text{Amount of solar energy received}}$$

The average latent heat of condensation of water vapour was taken to be 2326 kJ. kg^{-1} as suggested by Cooper[4].

The performance of unit 1 indicated that the average production rate of 2.50 $l.m^{-2}$ day^{-1} at mean solar radiation of 5.7 kW m^{-2} day^{-1} was similar to the results given in the United Nations reports[6], as well as that reported by Ong[7] of 2.40 $l.m^{-2}$ day^{-1} respectively. However, production was higher than the values of 2.01 $l.m^{-2}$ day^{-1} reported by Morse and others[8].

The difference in the results are most likely due to different designs of units and different test conditions.

The production rate of unit 2 is 20.30 percent higher than unit 1 which indicated the effectiveness of internal mirrors. Similarly, the average overall efficiency was 5.78 percent higher than unit 1. The performance of unit 3 was 58.20 and 37.90 percent higher than units 1 and 2 respectively. This substantial increase was due to the external mirrors. The optimum angle of adjustment of the external mirrors with respect to position of sun to yield maximum radiation flux was an important factor in the production efficiency. However, since the unit was manually operated, it was impossible to continuously adjust the mirrors. Automated tracking of the sun and adjustment would have increased the cost substantially. It has been reported[5] that external mirrors will result in a maximum concentration factor of 3. In this study a factor of 2.0 was used because the reflectivity of mirrors is always less than 100 percent.

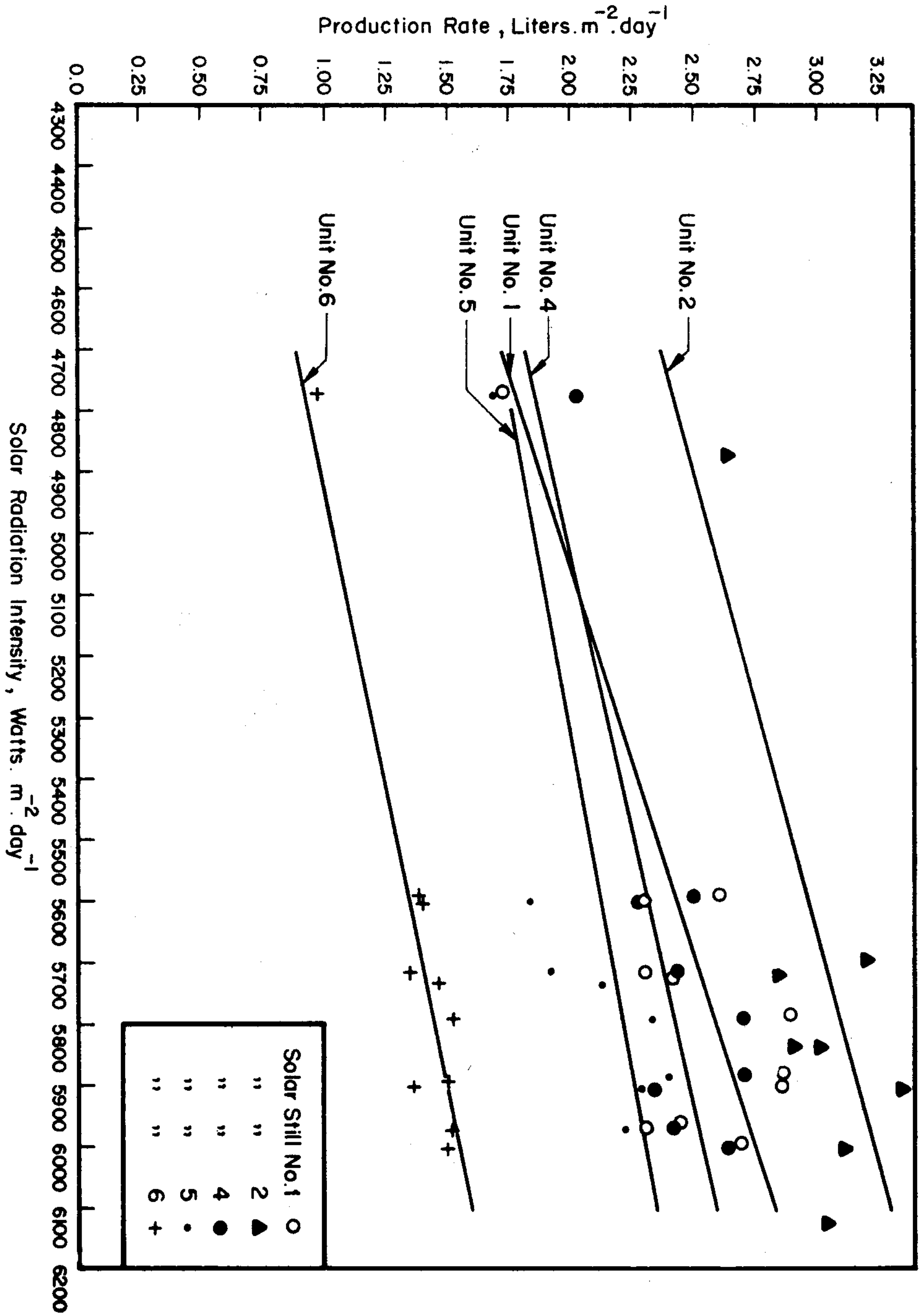


Fig. 4 Variation of Production Rate with Solar Radiation Intensity for Units 1,2,4,5 and 6

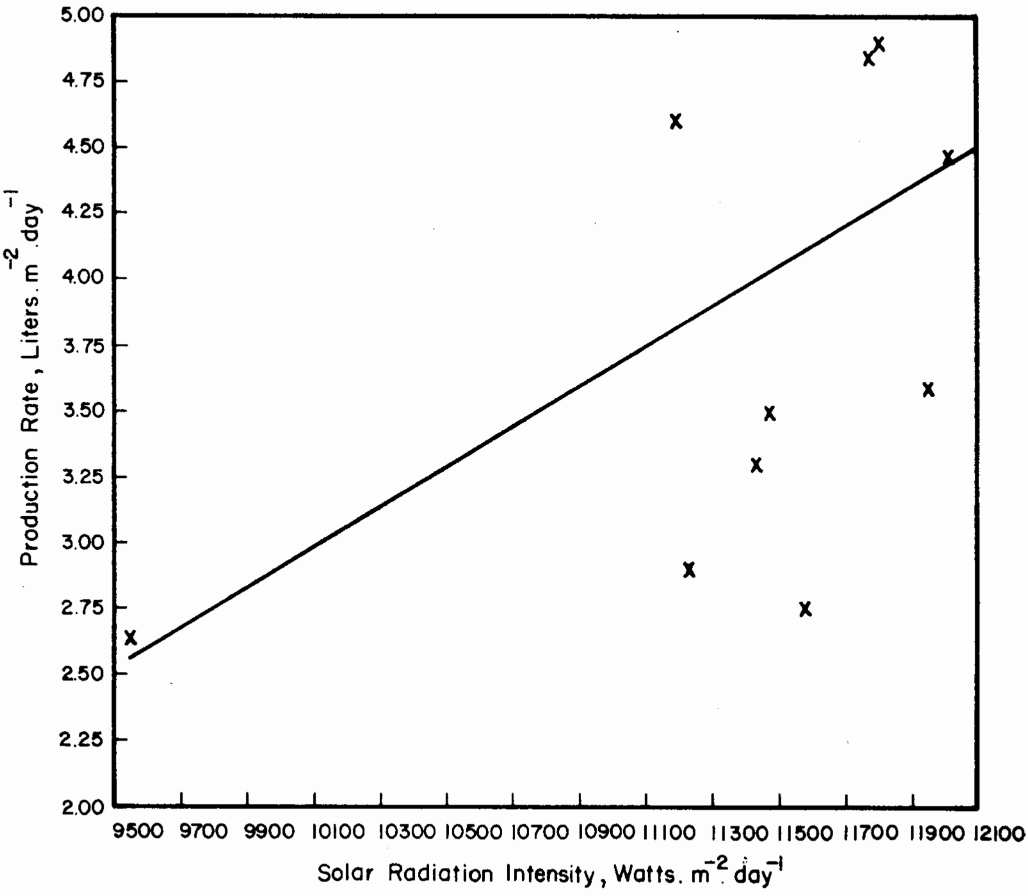


Fig. 5 Variation of Production Rate with Solar Radiation Intensity for Unit 3

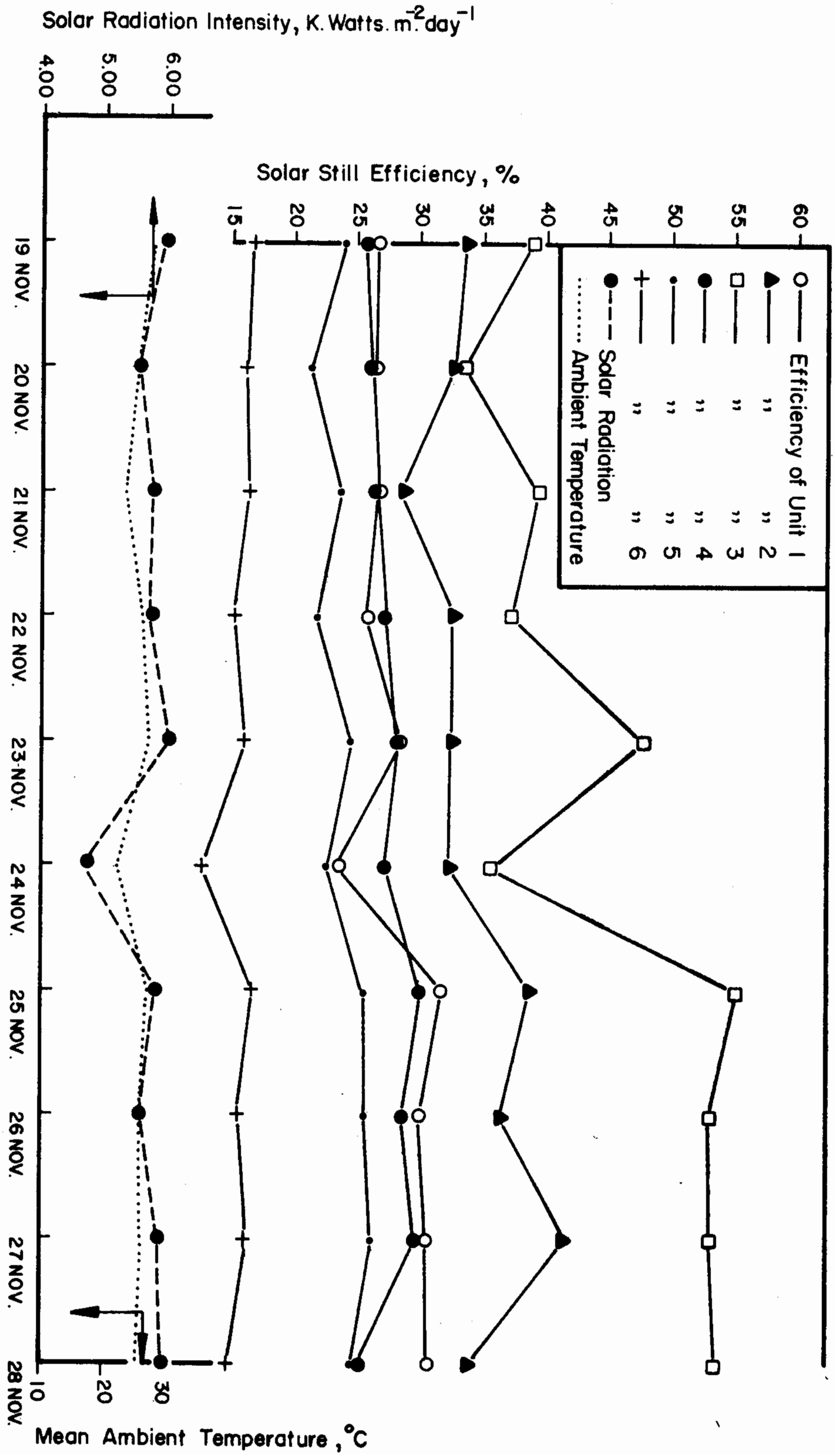


Fig. 6 Typical Solar Still Efficiencies

Units 4, 5 and 6 showed a decrease of 5.57, 13.34 and 44.22 percent respectively in the production rates and the overall efficiencies decreased by 1.59, 3.86 and 12.58 percent, compared with unit 1. This showed the negative effect of decreasing the depth/width ratio from 1:9 to 1:5, 1:4 and 1:3 respectively thereby causing extra shade by the side walls of the solar stills.

A semi-empirical relation to determine the internal heat transfer between glass cover and fluid surface by convection and evaporation has been reported[4]. From these heat transfer values, the evaporative efficiency as well as the ideal maximum overall efficiency, N_r could also be calculated.

Therefore for the conventional unit 1, the convective heat transfer can be determined from the relation:

$$q_c = 8.84 \times 10^{-4} \left[T_w - T_{gi} + \left(\frac{P_w - P_{gi}}{268.9 \times 10^3 - P_w} \right) (T_w) \right]^{1/3} (T_w - T_{gi}) \qquad (1)$$

where, q_c = convective heat transfer, kW m^{-2}

T_w = water surface temperature, K

T_{gi} = internal glass temperature, K

P_w = vapour partial pressure at T_w, Nm^{-2}

P_{gi} = vapour partial pressure at T_{gi}, Nm^{-2}

Substituting the calculated average values of T_w and T_{gi} from Fig. 3 in equation (1)

$$q_c = 8.84 \times 10^{-4} \left[(318) - (313) + \left(\frac{72 \times 133.32 - 55.4 \times 133.32}{268.9 \times 10^3 - 72 \times 133.32} \right) (318) \right]^{1/3} \times [(318) - (313)]$$

$$q_c = 0.00875 \text{ kW m}^{-2}$$

Also, the evaporative heat transfer can be determined from:

$$q_c = 16.276 \times 10^{-3} \, q_c \left(\frac{P_w - P_{gi}}{T_w - T_{gi}} \right) \qquad (2)$$

where q_c = evaporative heat transfer, kW m^{-2}

Substituting the values in equation (2)

$$q_c = 16.276 \times 10^{-3} \times 0.00875 \times \left[\frac{72 \times 133.32 - 55.4 \times 133.32}{(318) - (313)} \right]$$

$$q_c = 0.06303 \text{ kW m}^{-2}$$

To calculate the evaporative efficiency at a specific time, which can be for the condition when the still has reached average temperature, the solar radiation received on a horizontal surface at that time has to be determined. This can be calculated from:

$$G_h = \frac{G_T \pi}{7.2 \times 10^3 \, \theta_s} \sin \left(\frac{\pi \, \theta}{\theta_s} \right) \qquad (3)$$

where, G_T = total solar radiation on horizontal surface from sunrise to sunset, kJ m^{-2}

θ = time from sunrise, hours
θ_s = time from sunrise to sunset, hours
π = constant

The average temperature state reached by the fluid surface, T_w and the glass surface T_{gi} occurred at approximately 1000 hours, that is, 3.5 hours after sunrise. From Fig. 3 it can also be seen that the average temperature conditions occurred at 1700 hours as well, because the temperature variation with time is in the form of a parabolic sine curve.

Therefore θ = 3.5 h
when θ_s = 12 h and G_T = 5.28 kW m^{-2}d (average of maximum and minimum radiations)

Substituting these values in equation (3),

$$G_h = \frac{5.28 \times 3.6 \times 10^3}{7.20 \times 10^3 \times 12} \times \sin\left(\frac{\pi \times 3.5}{12}\right) \text{ kW m}^{-2}$$

$$G_h = \frac{5.28 \times 3.6 \times 10^3}{7.20 \times 10^3 \times 12} \times 0.79335 = 0.54 \text{ kW m}^{-2}$$

Not all the solar radiation that is incident on the horizontal surface is absorbed by the still. Hence the effective absorptance αa represents that portion of solar radiation which is productively absorbed and utilised in the various heat transfer modes from the glass cover to the saline water. It has been reproted[4] that for latitudes from 0 to 45 degrees and cover slopes ranging from 0 to 60 degrees, there is little variation in the radiation productively absorbed. A typical value for αa has been suggested to be 80 percent, after taking into account the angle of incidence.

The Evaporative Efficiency N_E is therefore, $\frac{q_e}{G_h} \alpha a = \frac{0.06}{0.54} \times 0.80 = 8.80$ percent

The calculated evaporative efficiency of 8.8 percent is significantly lower than the actual determined average overall efficiency of 27.8%. As reported[4] there is some doubt as to the validity of assumptions in the derivations of equations (1) and (2) for estimating the internal convective and evaporative heat transfer in the experimental solar stills. The difference is an order of magnitude of about three. The ideal maximum overall efficiency N_I of a conventional solar still is given by the relation:

$$N_I = 0.727 - 2.88 \times \frac{\theta_s}{G_T}$$

Substituting, θ_s = 12 hours

G_T = $5.28 \times 3.6 \times 10^3$ kJ m^{-2}

$$N_I = 0.727 - 2.88 \times \frac{12}{5.28 \times 3.6 \times 10^3}$$

∴ the ideal maximum overall efficiency=54.5%

This ideal maximum overall efficiency is based on the assumption that unit 1 is an "ideal still" which has no conductive losses and the fluid depth is sufficiently small so that sensible heat stored is negligible compared with the energy transfer rates to and from the fluid. For a given ambient temperature, wind velocity and solar radiation rate such a still will instantaneously reach steady state condition. The actual average overall efficiency over a day for unit 1 was found to be 27.8 percent and indicates actual conditions were different from the ideal.

Conclusions

With a mean solar radiation of 5.7 kW m^{-2} day^{-1}, a conventional solar still will produce 2.50 $l.m^{-2}$ day^{-1} of potable water. If internal or external mirrors are attached to the stills the production rates will increase to an average of 3.02 and 3.97 $l.m^{-2}$ day^{-1} respectively. These production rates correspond to 28.45, 34.23 and 45 percent efficiencies respectively. However, a calculated ideal maximum efficiency of the conventional unit was found to be as high as 54.5%.

An important still parameter that affects production rates and hence efficiency is the depth/width ratio of the still. Decreasing the ratio (i.e. increasing the depth) from 1 : 9 to 1 : 3 was found to have decreased the production rate by 44.2 percent.

Provided the angle of inclination of the glass cover was sufficient to allow the drainage of condensates for collection, the angle did not have any practical effects on the production rates of the still. In the study an angle of 13° 44" was used.

In the design, construction and operation of solar stills, heat losses and vapour leakage must be minimized to increase the efficiency.

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บทคัดย่อ

ได้บรรยายถึงการออกแบบและสร้างเครื่องกลั่นน้ำโดยใช้พลังแสงอาทิตย์ที่แตกต่างกันถึง 6 ชนิด พบว่าผลิตผลโดยเฉลี่ยจากเครื่องกลั่นดังกล่าว ประมาณ 2.50 ลิตรต่อตารางเมตรต่อวัน ประเมินประสิทธิภาพที่ได้ประมาณ 28.45 เปอร์เซ็นต์ กระจกที่ติดอยู่ด้านในและนอกเครื่องกลั่นจะให้ผลิตผลสูงขึ้น 20.32 และ 58.20 เปอร์เซ็นต์ตามลำดับ อย่างไรก็ตามหากลดความลึกและความกว้างของเครื่องกลั่นจาก 1:9 มาเป็น 1:3 จะลดอัตราการผลิตลงถึง 44.22 เปอร์เซ็นต์