Design and characterization of a solar-powered water distiller

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We describe the design and performance of a solar-powered still. It works on the simple principle of using solar energy to evaporate water, and then condense it on an inclined glass surface. We have considered many parameters for improving its performance while keeping the constraint of a low cost. The optimized still has an area of 0.4 m^2, and can produce about 1.5 l of pure water per day. The cost of making the still *at retail prices* is about ₹ 2000. Muddy rainwater and super-saturated salt water have been purified using the still. Tests conducted on the output samples shows that it is completely potable.

PACS numbers:

I. INTRODUCTION

The search for extra-terrestrial life starts with the search for the presence of water, because it is the most essential component for life (as we know it) to exist. Take away one energy source and nature will find an alternate source for survival. But take away water, and you will be left with a lifeless desert. Human beings—an integral part of the animal kingdom—are no exception. With rising global pollution levels and with our planet facing a looming ecological crisis, access to fresh water is going to determine the future of the human race. Water from underground water tables and aquifers that have been laid down over millions of years is being used at an unsustainable rate due to the indiscriminate use of borewells. Mountain glaciers, which are the source of many rivers, are shrinking due to global warming. Even when access to water is adequate, its purity remains a problem. It is no surprise that even in today's modern world, millions of children die every year in so-called developing countries because of using contaminated water, which causes diseases such as cholera, typhoid, and dysentery. Most of these lethal diseases can be prevented using simple precautions like boiling of water, but the poor do not have the resources for it.

In this article, we discuss the design and operation of a solar water purifier that achieves the above goal of making water potable and free of bacterial contamination. The idea is to use the energy of the sun to evaporate water, and then condense the vapor on an inclined glass surface. The glass surface plays the additional role of sealing the water contained inside while allowing the sun's rays to enter in. The design of the still has been optimized with the constraint of keeping a low cost that is affordable to the poor. In particular, it is a single-slope design [1], which is comparatively easy to fabricate. The optimized still has an area of 0.4 m^2 can produce up to 1.5 l of pure water per day. This is close to the maximum amount of water [2, 3] which can be produced from a still of this area for the given local insolation. The cost of making a one-off still—at retail prices—is only ₹ 2115 (equivalent US$ 38 at the current exchange rate), making it quite affordable for the target consumer.

II. DESIGN OF THE STILL

In the following, we present details of the various design parameters that were considered for optimizing the performance of the still. The stills were constructed by bending a sheet of galvanized iron (GI), since it was low cost and easily available. The inside was painted with black paint to absorb the incoming radiation and prevent corrosion. The dimensions on the back and sides were adjusted so that the top cover was inclined at the desired angle. The typical angle was chosen to be 13°, which is the latitude of Bangalore where all the experiments were done. This choice ensures that the sun's rays will be closest to normal incidence *averaged over one year*. The distilled water was collected in a channel along the front side. The size in the following tables refers to the cross section presented to the sun, with the first dimension giving the length of the side along which the water drops travel to reach the channel.

(i) *Effect of insulation*

Model	Size	Angle	Insulation
1	0.7 m × 0.5 m	13°	Styrofoam
2	0.7 m × 0.5 m	13°	None

To study the effect of insulation, we built two identical stills with the above specifications—one with 10 mm thick styrofoam insulation on all sides, and the second non-insulated. The insulated model gave 17% more output. The reason is that the insulation prevents heat loss from the still. Therefore, all the experiments below were done with insulated stills.

(ii) *Cover material*

Model	Size	Angle	Cover
1	0.7 × 0.5	13°	Plexiglas
2	0.7 × 0.5	13°	Glass

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Two kinds of common transparent materials were tried for the cover: glass and plexiglas. Glass has the advantage of good transmission of the solar spectrum but is breakable. Plexiglas—the trade name for poly methyl methacrylate (PMMA)—is a clear plastic that is almost unbrakable. When we built these two models for comparison, we found that even though the water-vapour condensation rate was faster in the plexiglas model (probably because of its lower temperature), there was no measurable water collection. In other words, the water vapour was condensing but not *flowing* on the plastic surface. In addition, the cover was getting *warped* after some time. This led us to conclude that plexiglas was not a good choice.

(iii) *Cover-glass thickness*

Model	Size	Angle	Thickness
1	0.7 m × 0.5 m	13°	3 mm
2	0.7 m × 0.5 m	13°	5 mm

The logic behind using a thinner cover glass is that it allows for more efficient heat transfer from the inside of the still to the ambient, and hence a lower temperature for the cover. This should result in more efficient vapour condensation and water collection. As expected, Model 1 with the 3 mm glass gave about 5% more output compared to Model 2. However, given the increased fragility of the thinner glass and the rather marginal improvement, we decided to stay with the 5 mm glass for our final design.

(iv) *Volume of water inside.*

Model	Size	Angle	Volume (Depth)
1	0.7 m × 0.5 m	13°	2 l (5 mm)
2	0.7 m × 0.5 m	13°	4 l (10 mm)
3	0.7 m × 0.5 m	13°	6 l (15 mm)

The total volume of water in the still is expected [4] to be an important factor affecting the output because it determines the heat capacity of the water, which has to be overcome before significant evaporation starts. Therefore, we tried amounts varying from 2 l (water depth of 5 mm) to 6 l (water depth of 15 mm). As expected, the smaller volume (or depth) gave proportionately more output. Therefore, we were led to a design where the water depth was kept as small as possible, and an external reservoir was used to maintain this level with a float valve. However, this design gave us *less* output. Upon careful analysis, we found that this was because there was too much heat loss into the reservoir through the connecting tube. We decided that a still with a fixed volume of water would perform the best. The volume was chosen to be 25% more than the daily output. This means that if the still produces 1.5 l/day, the total impure water would be 2 l. Once a day the pure water would be harvested and the impure water replenished. This was the only intervention required.

(v) *Use of preheater*

Model	Size	Angle	Preheater
1	0.7 m × 0.5 m	13°	Solar
2	0.7 m × 0.5 m	13°	None

A commercial solar water heater heats the water to about 75°C. If such preheating could improve the performance of the still significantly [5], it could justify the additional cost of the water heater. We therefore installed a commercial, 100-litre capacity, evacuated-tube solar heater, and channeled the water into the still through this preheater. The cost of the water heater was ₹ 12,000. Though the water output of the still increased by 35–40% compared to the non-preheated still output, the increase was too small to justify the additional cost. See the section on costing for further details.

(vi) *Aspect ratio*

Model	Size	Angle
1	0.7 m × 0.5 m	13°
2	0.4 m × 1.0 m	13°

Considering the way in which the water had to travel along the glass surface before being collected, it was felt that the collection would be larger is this distance was reduced. Therefore, we built two stills—one with aspect ratio of 7 by 5, and the other with 4 by 10—so that the travel distance was reduced from 0.7 m to 0.4 m. The comparison was done after normalizing for the increased area of the second still. As expected, the second still gave an increase of 8–10%. Further reduction in size was not considered because the cover glass would have become too unwieldy.

(vii) *Shadow effect*

Model	Size	Angle	Sides
1	0.4 m × 1.0 m	13°	GI
2	0.4 m × 1.0 m	13°	Plexiglas

In the models used in the above experiments, we saw that some part of the still was covered in shadow (due to the opaque GI sides) during the early and latter parts of the day. Hence, we built a second model of the same size, but with the GI sides replaced with transparent plexiglas. But we observed that the water vapour was also condensing on the plexiglas sides, most probably because the plexiglas was at a lower temperature compared to the GI base. This water was lost since it did not make it to the channel to be harvested. Hence, this model was rejected and we reverted back to the previous design of bending a GI sheet into the right shape. However, the overall height of the still was reduced to the maximum extent so as to keep the shadow as small as possible.

(viii) *Angle of inclination*

Model	Size	Angle
1	0.4 m × 1.0 m	10°
2	0.4 m × 1.0 m	13°
3	0.4 m × 1.0 m	16°

Recall that the canonical angle of the cover of 13° was chosen to match the latitude of Bangalore, which gives the best angle of incidence for the incoming rays averaged over the year. To study how much variation in output is caused by using a different angle, we built three models—with angles of 10°, 13°, and 16°, respectively. The water output of the three models measured for three days in the month of June are listed in the table below. Each reading (taken simultaneously on all three models) was taken after a few hours of operation in the morning.

	Water collected (cc)		
Date	10°	13°	16°
June 23	400	400	400
June 26	435	450	440
June 27	410	420	385

The readings show that there is no significant difference in the operation of the three stills. This leads us to conclude that the same angle of still can be used in all tropical countries with no significant change in performance.

(ix) *Base material*

Model	Size	Angle	Base
1	0.4 m × 1.0 m	13°	Sand
2	0.4 m × 1.0 m	13°	Gravel
3	0.4 m × 1.0 m	13°	Charcoal

To improve the heat absorption and retention by the still, we tried different materials on the bottom—sand, gravel, or charcoal. The comparison was made by measuring the total amount of water produced after 24 hours, to give enough time for the heat captured during the day to continue to produce water during the night. Model 2 with *the gravel base* gave the maximum output. An additional advantage of gravel is that it acts as a natural filter, and gravel beds are often used as filters in rainwater harvesting units. Therefore, we decided to use gravel as base material in our final design.

In summary, we have tried many parameters to improve the performance of the still. The three most significant ones are adding insulation around the sides and bottom, changing the aspect ratio, and using gravel on the bottom. Other parameters either did not work or resulted in marginal improvement.

III. PERFORMANCE OF THE STILL

We analyzed the performance of the still in two ways. First, we used it to purify muddy rain water collected from a puddle in the ground. The photograph below shows the water before and after purification with the still. The quality of the water is dramatically improved after purification, and it becomes crystal clear and potable. The water was tested before and after the purification. Next, we saw how effective the still was in making salty or brackish water potable. For this, we started with water that was saturated with salt, and "desalinated" it with the still. All the salt was left behind in the base of the still and the output water was completely salt-free. The water was again tested for various contaminants.

The test report on the rain water sample before and after purification are listed in Table 1. Also listed are the measurements on the water sample that was desalinated by the still. The measurements were done at a local laboratory—Indian Scientific Lab Products, Bangalore. The water was tested for all the contaminants that define potability as per IS:10500-1991 standards. The clear inference is that the water output from the still is *potable*.

IV. COSTING OF THE STILL

The cost (in ₹) of the various components used in fabricating the still are listed in the table below. These are costs for one-off procurement and fabrication in Bangalore. They can be expected to be much smaller for large quantities in a manufacturing unit. Despite this, the total cost per unit is only ₹ 2115, making it an affordable investment for anyone.

Item	Cost
1. GI sheet (1500 × 800 × 1 mm)	750
2. Glass (1020 × 460 × 5 mm)	285
3. Insulation foam (1500 × 800 × 8 mm)	80
4. Fabrication (Bending and Welding)	550
5. Powder Coating (Matt black)	350
6. Others (Hose nipple and Paper clips)	100
Total (₹)	2115

TABLE I: Test report of water before and after purification with the still.

Parameter	Permissible limit as per IS:10500-1991	**Rain water Input**	**Rain water Output**	**Salt water Output**
1. Colour — Hazen units	5	8.00	Colourless	Colourless
2. Odour	Unobjectionable	Odourless	Odourless	Odourless
3. pH value	6.5 to 8.5	7.85	6.95	6.85
4. Turbidity — NTU	5	8.50	< 0.01	< 0.01
5. Total dissolved solids — mg/l	500	340.00	95.00	140.00
6. Suspended solids — mg/l	150.00	160.00	< 0.01	< 0.01
7. Total hardness (as $CaCO_3$) — mg/l	300	240.00	20.00	30.00
8. Calcium hardness (as Ca) — mg/l	75	56.00	4.80	7.20
9. Magnesium (as Mg) — mg/l	30	24.00	1.90	2.80
10. Chlorides (as Cl) — mg/l	200	85.08	42.50	56.70
11. Sulphates (SO_4) — mg/l	200	< 0.01	< 0.01	< 0.01
12. Iron (as Fe) — mg/l	0.1	3.85	< 0.01	< 0.01
13. Nitrates (NO_3) — mg/l	Maximum 45	4.00	3.00	3.50
14. Total alkalinity (as $CaCO_3$) — mg/l	200	150.50	31.80	53.00
15. Fluorides (F) — mg/l	1	0.03	< 0.01	< 0.01
16. Copper (as Cu) — mg/l	0.05	< 0.01	< 0.01	< 0.01
17. Lead (as Pb) — mg/l	0.05	< 0.01	< 0.01	< 0.01
18. Zinc (as Zn) — mg/l	5.00	< 0.01	< 0.01	< 0.01
19. Manganese (as Mn) — mg/l	0.05	< 0.01	< 0.01	< 0.01
20. Total residual chlorine — mg/l	0.2	< 0.01	< 0.01	< 0.01
Inference	–	**Unfit for drinking**	**Fit for drinking**	**Fit for drinking**

V. CONCLUSION

About 20 pieces of the optimized solar still, with the above specifications, were fabricated locally. The photograph of the still is shown below. It produces up to 2 l of pure water per day. The stills have been distributed to few people near Bangalore for field tests and feedback on usability. It is otherwise ready for commercial production.

Acknowledgments

This work was supported though a partnership between Indian Institute of Science and the company Suryagen Renewable Energy Pvt Ltd.

[1] For a comparison of various designs, see for example— G. N. Tiwari, K. Mukherjee, K. R. Ashok, and Y. P. Yadav, "Comparison of various designs of solar stills," Desalination **60**, 191–202 (1986); or A. E. Kabeel and S. A. El-Agouz, "Review of researches and developments on solar stills," Desalination **276**, 1–12 (2011).
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