A Solar Still for Sophomore Design

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Abstract

A six-week long team project (design, build and test a solar still) conducted in a sophomore design course is described. Eight stills were constructed and then tested during a four-hour period around solar noon under very good solar conditions. The performances of the individual stills were quite varied (based on efficiency and expected water collection), but the average performance was close to the expected performance based on information available in the literature. However, the costs for these one-time devices were about double the value suggested in the literature. Evaluations of the stills conducted by both the students and the instructor and results from a student survey related to the project are presented.

Introduction

A sophomore level course, "Introduction to Mechanical Design", has been a required course for mechanical engineering majors at the University of Houston since 1980. Since 1990 it has been taught each fall and spring by the author of this paper. The course is usually the first engineering course taken by a mechanical engineering student. Therefore, part of the course objective is to introduce students to, and build their confidence in, problem-solving. The course is project-oriented, and during a typical semester one major team project (four-person teams) and two or three minor projects (individual or team) are assigned. The team projects normally require the designing, fabricating and testing of a kinematic device that throws, transports, and/or sorts items (e.g., golf balls or blocks) on a timed basis. Among the deliverables are: a working device which satisfies a set of constraints and performs satisfactorily, written progress reports, team meetings with the instructor, initial testing (proof of concept), final testing in which success in approaching specified goals is measured, a final written report, a final oral presentation and a design evaluation. Further details on past projects and the course can be found in References 1 through 7.

The Solar Still Project

In the spring of 2007 a “change of pace” team project (four-person teams) was assigned: the design, construction, and evaluation a solar-driven, water desalination device, i.e., a solar still. (See the complete assignment in the Appendix.) Aside from satisfying the traditional “hands-on”, team project requirements for the course, the project also required students to become familiar with two major natural resources potentially soon to be in short supply in both the country and the planet: water and energy, specifically potable water and renewable energy. Before beginning the team project, students had to select one of these two resources, focus on either the USA or the world, and prepare a report on the availability of it, the demand for it, and the prospects for meeting this demand in the near and distance future. About one-fourth of a report on water should discuss the technology of (artificial) desalination and its impact on future water supplies. About one-fourth of a report on energy should discuss the current and potential (direct) uses (collected by means of both thermal conversion and photovoltaic effect) of solar energy (i.e., not including wind, hydro-electric, ocean currents, etc.) to meet future energy needs.

The only restrictions on the materials for the still were that they must be common building/construction materials similar to those that could be purchased at a builder’s supply or home improvement store. The only restriction on size was that the aperture of the still should be less than 1.00 m^2. Projects were evaluated by calculating a figure of merit, FoM, that favored:

- efficient collection of distilled water,
- light weight and
- low cost

as shown in the eqn. (1) (Note that the effect of the “bonus points” used in the project are not included in this description.):

$$\text{FoM} = [4\eta/\eta_{avg} + 2W^*/W^*_{avg} + \$^*/\$^*_{avg}]/7 \tag{1}$$

where

η = performance efficiency: energy collected over the four-hour testing period that was actually used to evaporate water (i.e., the mass of distilled water collected times the heat of vaporization per unit mass of water) divided by the insolation on the still’s aperture during the same four-hour testing period (to be provided by the instructor).

W^* = total weight of the still per unit area of aperture

$\$^*$ = total cost of still materials per unit area of aperture

Subscript “avg” = class average

Results

The plan was for the testing to take place approximately during the class time on Monday and Wednesday, April 2nd and 4th, for the two hours either side of solar noon. The class normally met Monday and Wednesday from 9 AM to noon. Solar noon is at 1:25 PM

CDT in Houston the first week in April; so testing was set for 11:25 AM to 3:25 PM with set up beginning about 10:00 AM. A sight was selected just to the south of the Architecture building at the northern end of a service road which provided an unobstructed view of the sun for the four hours around solar noon. There were trees to the east and west but with proper planning the stills could be placed such there would be no shading during the testing period.

Normally, March and early April are "sunny" times for Houston (as are late September and October). Unfortunately, the spring 2007 was an unusually wet and overcast time for Houston. Testing had to be limited to one day and postponed to Monday, the 9th. However, the 9th was a "perfect" day with an essentially constant global, horizontal, total insolation of about 900 W/m^2 (as monitored throughout the testing with an Eppley PSP pyranometer) for the four-hour testing period except for the slight "cosine" effect.

The photographs in Figures 1 through 4 were taken on the day of testing (April 9, 2007). Figure 1 is an overview of the area showing some of the student traffic. (As part of the project each team had to prepare a brochure on distillation in general and its solar still in particular. Teams were told to bring about 20 copies to the testing to distribute to passing students. Of the eight stills, four were of "conventional design" (Figure 2), two very small (the one in the foreground in Figure 3), and two very different (Figure 4). Some physical parameters for the stills and the test results for the eight teams are given in Table 1. As seen in the table, the average aperture area projected horizontally, A, was 0.54 m^2; the average weight for a still, W_s, was 19 pounds; and the average cost was $81. The amount of solar energy incident on each aperture, E, based on a nearly constant 900 W/m^2 horizontal, total, global insolation during the testing , varied from 1.33 to 11.7 MJ. The amount of water, W_w, distilled and recovered in the four hours ranged from 5 to 50 ounces. The still efficiencies, Eff, (defined as the ratio of energy to evaporate the water collected to the insolation striking the aperture, Eff) ranged from 3% to 49% with average of 26%. The Figures of Merit, FoM, ranged from 0.53 to 1.52. Perhaps a better measure of performance would have been the cost per pound of water collected as presented in the second to last column in Table 1. The bottom row in the table presents values[8] for "typical solar still performances in sunny regions" (modified to half a day). Reference 8 cites 18 MJ/(day-m^2) as typical total, global insolation on a horizontal surface; ours was about 13 MJ/m^2 in just four hours, but around solar noon. In any event our average efficiency was very close to the expected value (Apparently teams 2, 6 and 7 were doing something illicit.). Our average costs per square meter were about double the "commercial" costs. As the results for efficiency indicated, the average volume of water collected per square meter was at the expected value (perhaps inflated by the unexplained high values reported for teams 2, 6, and 7).

Fig. 1: Testing Solar Stills on University of Houston campus April 9, 2007

Fig. 2: Two Conventional Designs

Figure 3: A Small Design (in the foreground)

Figure 4: Two Unconventional Designs

Evaluation of Design

Students were asked to evaluate the eight collectors using the rubric:

- Overall Impression: How does it look? Does it look like it will work? (30%)
- Performance: Does it appear to be working effectively? (20%)
- Robustness: Does it look like it will continue to work? (20%)
- Innovation: Does this still have an innovative design? (20%)
- Quality: How do you rate the overall quality of the device? (10%)

Table 1: Scoreboard for Testing of Solar Stills (for Four Hours of Testing)

Team	A	E	W_w	Eff	W_s	W_s/A	Cost	Cost/A	FoM	Cost/W_w	Vol/A
	m^2	MJ	oz		lbs	lbs/m^2	$	$/$m^2$		$/lb	Liter/m^2
1	0.39	5.0	11.5	0.17	25	64	101	260	0.53	140	0.9
2	0.10	1.33	9.0	0.49	3	29	24	233	1.52	16	2.6
3	0.55	7.1	24.	0.25	12	22	72	131	1.13	47	1.3
4	0.87	11.2	42.	0.27	26	30	93	107	1.13	35	1.4
5	0.58	7.5	11	0.11	30	52	75	129	0.60	110	0.6
6	0.81	10.5	50.	0.34	35	43	142	174	1.13	46	1.8
7	0.11	1.42	8.5	0.43	4	36	34	308	1.28	64	2.2
8	0.91	11.7	5.0	0.03	19	21	106	117	0.67	340	0.2
avg	**0.54**		**21**	**0.26**	**19.3**	**37.1**	**81**	**182**	**1.00**	**100**	**1.2**
ref 8*	**1.00**	**9****	**22**	**0.25**				**100**			**1.3**

* "typical" solar still performances in sunny regions (based on half a day)
**half a day

A = horizontal projection of the aperture area, m^2
E = solar energy incident on aperture (insolation measured throughout testing times A), MJ
W_w = distilled water collected outside still, oz
Eff = estimated fraction of energy used to convert water to steam
W_s = weight of still, lbs
Cost = cost of materials for still, $
FoM = figure of merit as determined by Eqn (1)
Vol = volume f distilled water collected, liter

Students were told to assign ratings based on: "95 was great"; "85 was good"; "75 was average"; "65 was below expectations" and "below 50 was "poor". The results of the evaluations of the stills by the students and the instructor are summarized in Table 2. As seen in rows three and four, when evaluating the stills made by other teams, the students and the instructor were almost the same (71 vs. 72). However, students generally have an inflated opinion of their own still (about 20% above what othersthink). There is considerable variation in the evaluations, but if teams 2, 5 and 8 were removed from the process, there is close agreement among everyone.

A previous paper[9] compared student and instructor evaluations of 37 individually built "solar clocks" using an equivalent rubric. In both cases students were given similar instructions. (See above.) The results for the solar clocks were that the average self evaluation was 91 ± 8; the average "other" evaluation was 86 ± 4 and the instructor's evaluation was 68 ± 18. The students' assessments were considerably higher than the instructor's (about 26% higher) as compared to being essentially the same for the stills. The students who built the solar stills were told of the previous study, and it was "suggested" that they should be more objective in their evaluations. And in deed they were.

Table 2: Evaluation of Stills by Students and Instructor

still	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**avg**
self	88	86	94	79	91	83	81	78	85
all	81±12	60±18	83±15	67±16	56±20	82±15	75±16	61±20	71
inst	92	87	85	68	45	68	82	50	72
A %	-4.3	-1.1	11	6	102	22	-1	56	
B %	8.6	43	13	8	63	1	6	28	
C%	-12	-31	-2	-1	24	20	13	22	

Row 1: the eight stills are indicated
Row 2: self-evaluations of each still by those who made it (average rating of team)
Row 3: evaluations, with the standard deviation of the distribution, of each still by all students except those who made the still
Row 4: evaluations of each still by the instructor
Row 5: blank
Row 6: A self-evaluations compared to those of the instructor ((self-inst)/inst as a %)
Row 7: B self-evaluations compared to those of other students ((self-all)/all as a %)
Row 8: C student evaluation compared to those of the instructor ((all-inst)/inst as a %)

Student Survey

An end-of-the-semester, five-point Likert response, survey was administered, and the results associated with the solar still project are shown in Table 3. As seen in the table the students were almost "neutral" in their support for the "more relevant" design project compared to the "expected" project. However, only two indicated they didn't learn anything from writing the paper. The responses to the remaining statements are on average 0.22 lower than seven-semester average indicated in Table 4. Further, for the last seven responses related to the solar still project there is an 11% negative response (disagree or strongly disagree) compare to a 3.5% negative response indicated in the seven-semester average in Table 4.

Conclusions

A six-week long team project (design, build and test a solar still) conducted in a sophomore design course has been described. While the individual performances for the stills were quite varied, the average performance of the eight stills was very close to the expected performance based on information available in the literature. Given the fact that water and energy are certainly relevant issues both for the engineer and the citizen, it was a little disappointing that the students were measurably less enthusiastic about the still project than many other irrelevant, toss-the-ball-in-the-basket-like projects of the past.

Table 3: Results from End-of-the Semester Student Survey

Instructions: Select the number: 5 for strongly agree, 4 for agree, 3 for neutral, 2 for disagree, and 1 for strongly disagree that best characterize your opinions of the following statements; N is the number of responses and "avg" is the average of the responses

1	2	3	4	5	N	avg	statement
4	4	10	5	10	33	**3.39**	I would have preferred the usual "indoor" project over the solar still project
1	1	7	17	7	33	**3.85**	I learned something in writing the water/energy paper
2	2	4	11	14	33	**4.00**	I am proud of my team's effort
4	1	1	10	17	33	**4.06**	I am proud of my team's solution
		6	9	18	33	**4.36**	I liked the fact that their were peer evaluations
							I enjoyed
2	1	5	7	18	33	**4.15**	working on the solar still project
5	2	3	6	17	33	**3.85**	working on a team
2		6	7	18	33	**4.18**	the friendly competition between teams
2		5	7	19	33	**4.24**	seeing how others solved problems I struggled with
							I feel that I improved my ability to
1	4	3	12	13	33	**3.97**	design a system or component to meet desired needs
1	3	3	12	14	33	**4.06**	function on a team
	3	6	14	10	33	**3.94**	communicate effectively

Table 4: Results from End-of-the-Semester Class Survey (Fall 2002 through Fall 2005)

Instructions: Select the number: 5 for strongly agree, 4 for agree, 3 for neutral, 2 for disagree, and 1 for strongly disagree that best characterize your opinions of the following statements; N is the number of responses and "avg" is the average of the responses

1	2	3	4	5	N	avg	I enjoyed
3	7	22	99	169	300	**4.41**	working on the projects
8	11	35	99	147	300	**4.22**	working on a team
1	13	31	94	161	300	**4.34**	having friendly competition between teams
2	6	30	85	177	300	**4.43**	seeing how others solved problems I struggled with
							I feel that I improved my ability to
			140	132	300	**4.31**	design a system or component to meet desired needs
	9	31	129	131	300	**4.27**	function on a team
1	11	57	143	88	300	**4.02**	communicate effectively

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APPENDIX:
Handout Describing the Solar Still Team Project for Spring 2007

MECE 2361: Introduction to Design
Spring 2007

Team Project: Water and Energy

Assigned: February 12th
Form Teams: February 26th
Individual Report Due: March 5th
Team Prototype Presented for Testing: Week of April 2nd
Team Sales Brochure: April 2nd
Hard Copy of the Team Final Report Due: April 11th
Electronic Copy of the Team Final Report Due: April 11th

The Major Project has two components: an individual report (5% of the individual course grade) and a team activity (15% of the individual course grade) as described below.

Individual Report
Water and energy are two natural resources that are currently in limited supply, and shortages are expected in the future for both the USA and the rest of the world. For the "individual part" of this project, select one of these two resources, focus on either the USA or the world, and prepare a report (due March 5th) on the availability of it, the demand for it, and the prospects for meeting this demand in the near and distance future. Potential consequences should also be discussed. If you select water, about one-fourth of your paper should discuss the technology of (artificial) desalination and its impact on future water supplies. If you select energy, about one-fourth of your paper should discuss the current and potential (direct) uses (collected by means of both thermal conversion and photovoltaic effect) of solar energy (i.e., not including wind, hydro-electric, ocean currents, etc.) to meet future energy needs. The paper should have an abstract and conclusion and is limited to 3000 words. There is no need for a transmittal letter, cover page, or table of contents. Tables and figures are encouraged, and should be properly referenced and cited in the text. Place you name and course identification in the upper right hand corner of the first page; center and bold the title at the top of the first page; use left adjusted, bold headers (as in this document) for each section (including the abstract and the conclusions); and secure the pages with a staple in the upper left hand corner before submission (Do not use external covers).

Teams and General Instructions for Team Project

On February 26th we shall be forming four-person teams in class. These teams may be formed by the instructor based on place of residence, availability of resources and member skills or may be self-formed. Watch the class website for developments. The team project is to design, construct, and evaluate a solar-driven, water desalination device, i.e., a solar still. The only restrictions on the materials are that they must be common building/construction materials similar to those that could be purchased at a builder's supply or home improvement store, e.g., Lowe's, at a model or craft shop, e.g., Michael's, at an art supply store, or at a hardware store. An inventory and cost of materials purchased and used should be kept and presented in the form of a table at the Testing and in the Final Report. (See below.) Fair market value of materials "borrowed" should be reported. Items which individually cost less than $1 may be grouped under "miscellaneous". The only restriction on size is that the aperture of the still should be less than 1.00 m^2. The still must be weighed before the Testing so it must have sufficient strength to "survive" the weigh it, which may be on relatively small scale. You should strive for a still weighing less than 25 pounds.

Testing

The stills should be ready for testing by 9:30 AM (CDT) Monday, April 2nd. As this date nears, the actually testing times (days) will be determined based on weather forecasts. The intent is to test the stills during the best two "sun" days for the week (with preference given to Monday and Wednesday if possible) for at least the middle four hours of the day, i.e., about two hours either side of solar noon. Note that all stills must be tested at the same time to assure "equivalent" environmental conditions. The testing will consist of the following procedure. A general test site will be determined. Teams will set up their stills on the ground or appropriate "stands" by 9:30 AM solar time on the day of the testing. Teams will be allowed to replenish the salty water and to retrieve the distilled water every 60 minutes, and move or adjust the physical character of their stills at solar noon. Teams will be allowed up to three minutes to replenish/retrieve the water and five minutes to move or adjust their stills. (Lost collecting time due to these actions will NOT be made up.) The amount of water distilled will be determined each 60 minutes (by the instructor) just prior to the replenishment. It is the responsibility of the team to provide a container for the distilled water that allows for easy transfer to the instructor's standard measuring container. Each team shall provide a suitable container for storage of the distilled water produced for the entire four-hour testing period.

It is intended that the performance of the stills will be determined based on the results for two days of testing. If only one day of testing is utilized the first week due to poor "weather" (determined at the discretion of the instructor), then testing may be extended into the next week or terminated at the discretion of the instructor.

During the Testing at least one member of each team should be present with his/her still. If this attendance can not be arranged due to scheduling conflicts, the instructor should be notified in advance. The team member(s) present during Testing will be responsible for responding to questions and inquiries from the instructor (as part of the still evaluation as described below) and the general public (whoever happens to walk by). Each student in the class will also be expected to be present for at least two hours during the total of eight hours of testing. During the Testing period (but not during the times a student is "on duty" as his/her team's still watcher) each student in the class will complete an evaluation (criteria listed below) on each still including his/her own team's still. The team should prepare a "sales" brochure explaining the purpose and operation of a solar still in general (perhaps including some comments on the issue of the increasing scarcity of drinking water) and of its still in particular (pointing out its special features). The brochure should be addressed to an audience of high school seniors who have completed a year of high school physics and a year of high school calculus. At least 20 copies of the brochure should be brought to the Testing for distribution.

Performance Evaluation
The major goal of the design portion of the project is to produce an efficient (high performing), lightweight, low-cost device as determined by the value of a figure of merit (FoM) based on these criteria. The figure of merit will be evaluated with the following formula:

$$FoM = 100\ [4\eta/\eta_{avg} + 2W^*/W^*_{avg} + \$^*/\$^*_{avg} + PB + WB + CB]/7$$

η = performance efficiency: energy collected over the four-hour Testing period that was actually used to evaporate water (i.e., the mass of distilled water collected times the heat of vaporization per unit mass of water) divided by the insolation on the still's aperture during the same four-hour Testing period (to be provided by the instructor).
W^* = total weight of the still per unit area of aperture
$\$^*$ = total cost of still materials per unit area of aperture
Subscript "avg" = class average for one day of testing

PB = bonus points for efficiency: 0.2 for highest value of η; 0.15 for next highest and 0.1 for next and 0.05 for the next.
WB = bonus points for low weight: 0.1 for lowest value of W*; 0.06 for next lowest, and 0.03 for the next.
CB = bonus points for low cost: 0.05 for lowest value of S*; 0.03 for next lowest, and 0.015 for the next.

Design Evaluation
The still itself will be evaluated by the instructor and the members of the class while the still is operating. The criteria will be:

1. Overall impression: Is it impressive "looking"? Does it look as if it would work well, i.e., an impression based upon appearance alone of the still in a non-operating mode? 30%
2. Actual Performance: Does it appear to be working well? 20%
3. Reliability (robustness): Does it "look" like it would work after a couple of weeks of operations outside? 20%
4. Use of innovative features compared to others: Does it have useful design features absent from the other stills? 20%

5. Quality of craftsmanship: Is it “put together well”? Quality of fastening? Quality of construction? Non-functional esthetics?: 10%

Final Report

A Technical Report on the project will be submitted on April 11th. Additional details for the specific content will be provided later, but at a minimum the report will contain:

- An overview and history of solar stills,
- A description of the operation, analysis, and evaluation of solar stills,
- A description of the team’s design including drawings and/or photographs,
- Performance results for the team’s still, including FoM calculations from results obtained during the official Testing (most of this information will probably be provided by the instructor) and any independent testing by the team,
- A critical evaluation of the team’s still and recommendations for improvement in performance, cost, and/or weight,
- Copies of the team members’ Individual Reports (on Water or Energy) as appendices, and
- The sales brochure (as an appendix).

Grading

The team project (not counting the individual report on Water or Energy which counts 5%) counts for 15% of the course grade. Normally the team members share the “credit” and the grade equally. However, peer evaluations will be conducted and based on these (and the instructor’s) evaluations of team members, individual grades could be below or, in only rare cases, above the team grade.

30%	Performance (Credit will be given based on each team’s better day of Testing (the higher Figure of Merit) as compared to the performances of the other teams (i.e., the average of better Figure of Merits for all teams)
20%	Evaluation of the Design
15%	Brochure
25%	Final Report
10%	General attitude of the team (e.g., team “togetherness” and camaraderie, general knowledge expressed by the individual team members, individual critiques (evaluations) of the other designs, etc.) as determined by the instructor