AC 2011-687: SOLAR DISTILLATION PROJECT

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by

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1. Abstract

A solar design project has been developed for use at the United States Air Force Academy (USAFA) in a sustainable energy course; the project entails prediction of solar position, surface insolation intensity, heat transfer modeling of a solar distillation unit, and the possibility for more open-ended applications with other locations, environmental conditions, or system modifications. The course was offered for the first time in the spring of 2011, and included many different aspects of sustainable energy (wind, ocean, solar, geothermal, etc.; the topic which is covered first, and which receives more coverage than most others is solar (active, passive, photovoltaic), so that a solar project is deemed most appropriate. The project's purposes include: to reinforce classroom instruction in solar principles, to provide detailed modeling of the heat transfer process in a specific application (a solar distillation unit), to provide practice in modular programming, and to allow modification of the model for use in a variety of locations or to assess the impact of modifications to the system. The project is divided into stages, timed so that each is due shortly after the topic material is covered in class. While no feedback data are available, it is anticipated that the project will provide students with a practical application of the principles of basic thermodynamics and heat transfer, and of the specific principles associated with solar energy harvesting. Details of the project are provided, along with possible extensions and variations for future course offerings.

2. Background

A new course in renewable/sustainable energy has been developed for the mechanical engineering curriculum at USAFA, and is being taught for the first time in the Spring 2011 term. As opposed to many of the texts in the renewable/sustainable energy field, the text selected[1] provides a computationally intense basis for most of the topics in the course syllabus. Guest lecturers and a field trip to the National Renewable Energy Laboratory in Golden, Colorado also provide different insights and recent developments in the field. Engineering thermodynamics is a prerequisite, fluid mechanics is a co-requisite, and while an introduction to the basic modes of heat transfer are covered in the engineering thermodynamics course, it is recommended that enrolled students have satisfactorily completed a dedicated heat transfer course.

While the course covers a variety of topics (solar, wind, ocean, hydro, geothermal, combined heat and power, biomass, nuclear, etc.), a substantial portion of the course is devoted to solar energy (active, passive, and photovoltaic), and would benefit greatly from the incorporation of a student project which entails the use of the course material to further reinforce the text material.

Dixon[2,3] proposed a project to design, build, and test a solar distillation unit as part of a course in thermal systems design; the project included:

- Construction of a heat transfer model of the various heat transfer mechanisms involved, based principally upon the electrical analog of each heat transfer mechanism.
- Transient spreadsheet simulation of the system, based upon average hourly data for a specific geographic location, run for a 5-hour period.
- Fabrication and testing of a small solar distillation unit, with results of fresh water produced versus time compared to results obtained from the spreadsheet simulation.

3. Project Overview

While the input to the simulation proposed by Dixon was hourly average insolation based upon historical data for a specific site, a more extensive project is one which requires students to calculate actual solar position and intensity, and then to use these predictions as the input to a spreadsheet similar to that proposed by Dixon. Once verified against a standard set of data, students are then required to apply the model for use in other geographical sites, for environmental extremes, or to suggest and incorporate various design modifications to enhance system performance. The objectives of the project are:

- To reinforce course material in solar tracking.
- To provide experience in thermal modeling and modular programming.
- To provide students with the opportunity to incorporate design variations to improve system performance.

In the assignment of the project during the first offering of the course, students are not required to build and test a prototype distillation unit. One of the students taking the course is also enrolled in an independent study, the purpose of which is to build and test such a prototype to assess not only the time required to build such a unit, but also to amass data concerning parts required and associated funding. A determination will be made whether or not incorporation of such a fabrication project in future course offerings would be excessive in terms of student workload.

4. Project Details

The scenario presented to students is that a solar distillation unit is proposed for a southern California seaside location (nominally Vandenburg Air Force Base), and that the students are tasked with ascertaining the feasibility of such a proposal. The project consists of three parts:

1. Solar tracking and intensity calculations for the site on a specified date (nominally 21 June).
2. Transient thermal modeling of a prototype solar distiller to ascertain fresh water production as a function of time, with extrapolation up to a full-scale unit. Insolation is

provided from results obtained from the solar tracking data calculated in the first part of the project.

3. Design modification proposed by each team of 2 students and approved by the instructor, in an effort to improve the basic system or to apply the model for analysis in different locations, different environmental conditions, etc. Appropriate modifications are required to the basic model, with supporting analysis to determine the efficacy of the proposed modification. If the model is not modified, but used instead to determine the distiller performance at different locations or under different environmental conditions, then logical interpretations and recommendations must be made.

The first block in the course, of which the project is a major component, includes a rudimentary introduction to solar energy fundamentals, active and passive solar systems, and photovoltaics. The first part of the project (centered mainly about prediction of sun path) is introduced immediately following the first block; the first part of the project is due approximately 3 weeks after it was assigned.

The second part of the project (modeling of the solar distillation unit and simulation via a computer program) is phased so that it is due approximately 4 weeks after the first part. The timing was such that it was due after mid-term.

Each of the first two parts of the project is of a "closed form" nature, such that the answers were reasonably standard; since there are no teaching assistants at USAFA (a completely undergraduate institution), grading by the instructor is greatly facilitated. Additionally, when spreadsheets are chosen as the programming method, two hard copies are required for submission: one with cell calculation results shown, and the other with formulas displayed for each cell. Each submission is further required to have grid lines and column and row headings displayed to facilitate verification.

A more detailed description of each portion follows.

4. A. Sun Path Calculations

The objective for this part of the project is to ascertain, for a give date and location, the elevation and azimuth angles for the sun at any time. Calculation of the solar path is a well-known procedure, and is well-documented (Goswami *et al*[4], Hodge[1], Duffie and Beckman[5], and many others). In summary, inputs of date and location (latitude and longitude) are used to calculate Julian date, declination, extraterrestrial normal radiation, sunrise, and sunset.

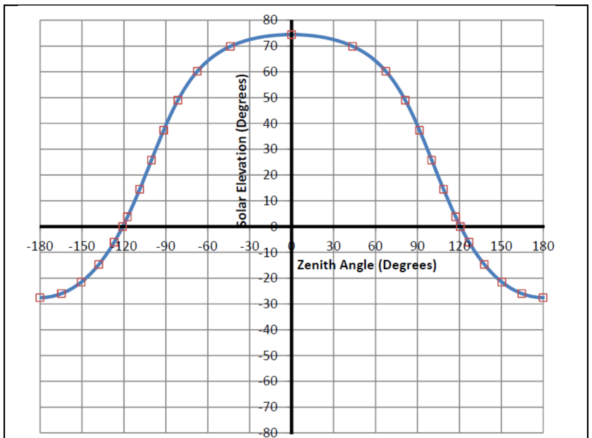

Figure 1: Sun path for June 21 at southern Vandenburg Air Force Base.

Once all the above calculations are verified, they are used to calculate, for any time during the given date, solar time, standard time, altitude angle, and azimuth angle. Results are then plotted to provide sun path (Figure 1), and students are then required to validate this against available resources (a plethora of online solar calculators, tabulated values, etc.). Each of the steps involved in this process presents a direct application of material presented in the text and/or classroom lectures.

Students are free to choose any software with which to perform these calculations, but most will likely opt for Excel™, due principally to its availability and their familiarity with the software. Regardless of the software utilized, they are required to employ modular programming, with individual program functions written for each major calculation; each function is required to be tested against easily verified results (either hand calculations or tabulated values). For those students who choose Excel™, the Visual Basic for Application™ (VBA) programming environment allows substantial modular programming capabilities beyond those available in normal spreadsheet formulas.

4. B. Thermal Modeling and Transient Simulation

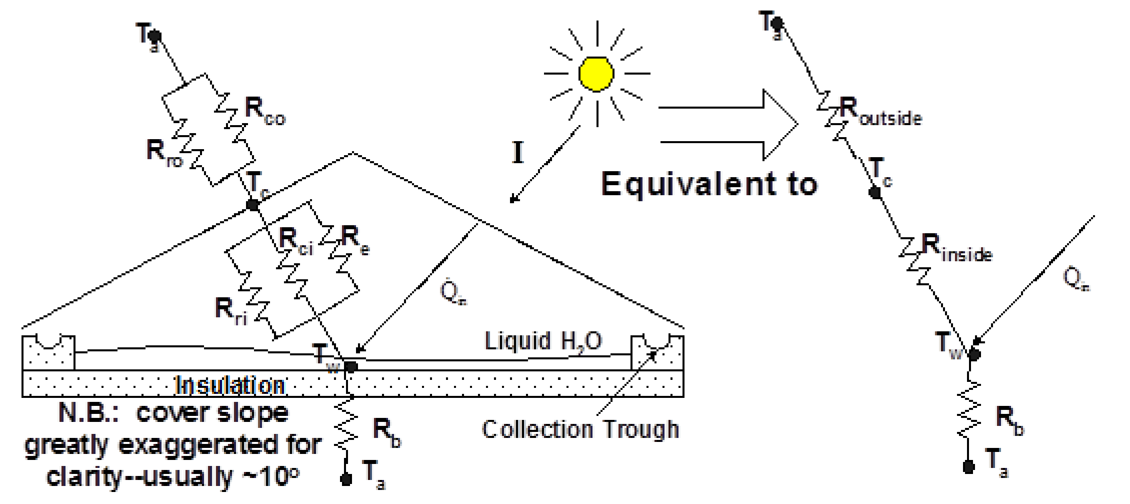

Figure 2: Schematic and equivalent electrical analog of heat transfer process associated with solar distillation unit (after Dixon[2,3], Goswami et al[4], and Duffie and Beckman[5].

Once the sun path has been determined, students are required to construct a model of a solar distillation unit; a suitable model is described by several authors[2,3,4,5], and a composite is provided in Figure 2. Extensive use is made of the electrical analogy to heat transfer, as described in most heat transfer texts. An earlier module in the course includes a brief introduction to the relevant aspects of solar radiation, including transmissivity, reflectivity, extraterrestrial normal radiation, and the like; additionally, a component of the required engineering thermodynamics prerequisite covers a basic introduction to all three modes of heat transfer (convection, conduction, and radiation). An introduction to the various analogies which can be drawn between heat transfer and the flow of electricity in an electric circuit is required:

heat transfer rate ~ electric current, thermal resistance ~ electrical resistance, and temperature difference ~ potential difference. In conjunction with a reading assignment along these lines, one or two lessons are spent in describing these concepts. Additionally, some students have taken a dedicated semester course in heat transfer, giving them a slight advantage; care is taken when pairing students into project teams to ensure that at least one student has had the heat transfer course.

Figure 2 shows there is radiation and convection heat transfer between the distillation unit cover and the environment, and also between the distilled water pool and the cover; additionally, an equivalent "evaporative" resistance exists between the distilled water and the cover (Goswami *et al*[4] and Duffie and Beckman[5] provide suitable correlations which may be employed to calculate this effect). Solar extinction (assumed for a clear day) reduces the normal extraterrestrial radiation to a value which is incident on the distiller cover (given its low slope, it is assumed to be horizontal); after application of a suitable value of transmissivity, the radiation transmitted to the distilled water may then be calculated. Finally, a small amount of conduction occurs through the insulated base to the environment. It is further assumed that the only item which possesses thermal capacitance of any significance is the distilled water; a suitable value of solar absorptivity is chosen for the distillation pool. Thirty-year averages for ambient temperature at hourly intervals have been obtained for the specified location, so that students may utilize these data to obtain realistic values.

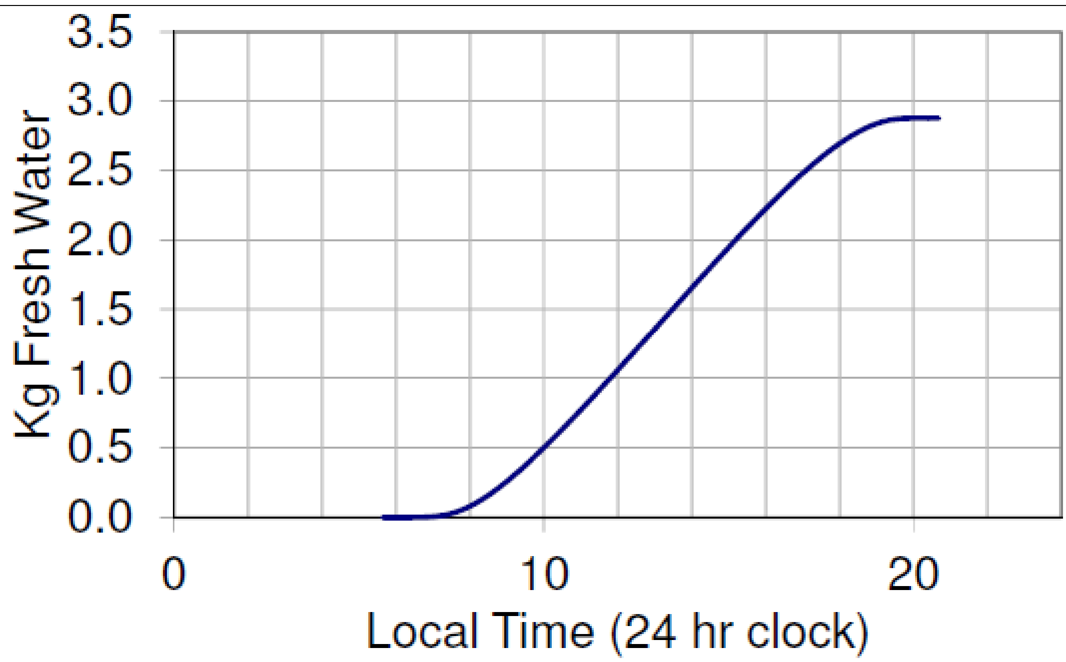

Figure 3: Representative plot of water production as a function of local time.

Initial conditions are assumed such that all temperatures are at the ambient temperature. Suitable program modules must be devised by the students to calculate: solar extinction (based on clear day conditions), direct beam and diffuse radiation, incidence angle modifier, values of all thermal resistances and associated heat transfer rates shown in Figure 2, and cover and water temperatures. Finally, the condensation rate (assumed to be equal to the evaporation rate) is calculated. A simple Eulerian timestep method is employed to simulate the transient nature of the problem. Finally, the volume of water produced is plotted as a function of local clock time; representative results are shown in Figure 3. Additional details of the model are provided by Dixon[2,3], Goswami *et al*[4], and Duffie and Beckman[5].

4. C. Design Modifications and Recommendations for Future Use

Once the second part is graded and returned to students, they are required to correct any problems and verify that they now have a tool which may be used for the third portion of the project.

Students are required to submit a proposed modification to the project, or to perform a parametric analysis for differing locations, environmental conditions, etc.; it is imperative that appropriate consideration is given to the proposal to ensure that it meets with a minimum degree of difficulty, while not exceeding the time and/or difficulty expected of such a project. Once approved by the instructor, students have the remainder of the term in which to complete the third portion of the project.

Possible modifications included the following:

- Different type of unit (parabolic trough, tower, etc.)
- Incorporation of single- or double-axis tracking.
- Determination of optimal brine depth (too deep requires too long for the salt water to heat up; too shallow, and it might evaporate too quickly).
- Determination of appropriate range of salt water depths.
- Determine how often and for how long should a brine feed pump should be activated.
- Incorporation of vacuum to facilitate water vaporization.
- Photovoltaic powering of associated pumps (feed, brine, vacuum, etc.)
- Recuperation of heat from brine discharge to salt water feed
- Impact of different location
- Impact of different atmospheric effects: cloud cover, cold/hot snaps
- Portability of the unit for assembly and/or disassembly

5. Design-Build-Test

The ultimate goal for this project in future terms would be to include fabrication and testing of a small solar distillation unit, as originally proposed by Dixon[2,3]. Since the course (of which this project is a part) is being offered for the first time in the Spring of 2011, it was decided not to include the fabrication and testing portion, but to gauge the time demands imposed by the project as outlined above. Additionally, however, one student has indicated a desire to perform an independent study associated with renewable energy; happily, this student will be enrolled in the course described above while engaged in the independent study project, so he will have the requisite exposure to the background necessary to understand the theory and functioning of the distillation unit. To ensure the independent study project contains the necessary rigor, that student will be required to perform additional research on solar distillation units, and to design, build, and test his unit. He will also be required to keep detailed records on all time entailed with fabrication and testing of his unit, in order to determine whether or not the build and test phase should be incorporated in future course offerings. Additionally, a detailed cost log will be maintained to determine the budget required for incorporation of this project; he will also be required to record atmospheric data during the testing of his unit, to include barometric pressure, ambient temperature, approximate cloud coverage, and wind speed data.

6. Conclusions

The project described herein provides a practical application and reinforcement of classroom material provided in the solar portion of a renewable energy course. A phased approach is undertaken, whereby students are required to first complete solar tracking calculations, and then apply those calculations as the input to a computer model of a simple solar distillation unit. Once complete, students are required to propose a design modification to the basic design criteria, and to ascertain system performance with that modification incorporated; alternatively, students may use the unmodified model to analyze performance of the distillation unit in different locations, under other environmental conditions, etc. Finally, a parallel independent study project is being conducted to ascertain the feasibility of expanding the project to include a build and test phase to further enhance the design phase of the project. While not a design course unto itself, students are still provided the latitude to perform additional research to either improve the model or to assess the performance of the distillation unit in various locations or under different environmental conditions.

7. Symbology

Symbol	Definition	Symbol	Definition
I	Solar power flux W/m^2)		Subscripts
$\dot{Q}$	Heat transfer rate (W)	A	Ambient
R	Thermal resistance (W/K)	b	Base
T	Temperature (℃, K)	c	Convection
		e	Evaporation
		i	Inner
		o	Outer
		r	Radiation
		w	water

References

[1] Hodge, B.K. 2010. *Alternative Energy Systems and Applications*, Hoboken: Wiley.
[2] Dixon, G.W. Three Thermal Systems Design-Build-Test Projects. *Proceedings of the 2004 American Society of Engineering Education Annual Conference and Exposition*, Session 2266.
[3] Dixon, G.W. A Solar Distiller as a Thermal Systems Design-Build-Test Project. *Proceedings of the 2006 American Society of Engineering Education Annual Conference and Exposition*, paper 2006-134.
[4] Goswami, D.Y., Kreith, F., and Kreider, J.F. 2000. *Principles of Solar Engineering*, 2nd ed., Philadelphia: Taylor & Francis.
[5] Duffie, J.A. and Beckman, W.A. 2006. *Solar Engineering of Thermal Processes*, 3rd ed., Hoboken: Wiley.