# Three Thermal Systems Design-Build-Test Projects

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Abstract:
In an effort to improve Mechanical Engineering (ME) students' ability to design and realize thermal systems, three hands-on design projects have been developed for a junior level thermal systems design course. The three projects involve giving small student teams the tasks of:

1. Heating water in a large coffee can using a natural circulation solar collector that the students design and construct.
2. Producing distilled water with a solar distillation device.
3. Heating water in a natural circulation loop using combustion of candle wax.

In all of the projects, the teams are given a limited set of materials and specifications that constrain their design options while giving them plenty of opportunity for creativity. The materials required are inexpensive (insulating foam, plywood, tubes, tape, reflective tape, hoses and hose clamps, etc.). The teams are required to develop conceptual designs and analyze their design in three successive levels of complexity before they are allowed to begin construction. Teams are required to evaluate alternatives and base design decisions on their analyses. The culmination of the projects is a test in which the students' systems are tested against their predictions and in which they compete to see which team's design performs the best.

These projects require students to develop their ability to integrate their knowledge of heat transfer, fluid dynamics and thermodynamics to develop models of their systems, which allow them to optimize their designs. Significant student-faculty interaction is generated through this exercise, and course evaluations indicate that students consider this to be a valuable experience, which increases their confidence in their ability to apply basic principles to the design of an actual thermal system.

Background:
In the current undergraduate ME program at the U.S. Coast Guard Academy, students have more opportunity to design and construct mechanical systems than they do thermal systems. The ABET program criteria for Mechanical Engineering[1] require students to demonstrate an ability to design and realize both types of systems. The development of three different projects has allowed annual rotation of project assignments which are designed to achieve common objectives consistent with ABET criteria. The stages of analysis required before students can begin construction involve:

- "Back of the envelope" calculation of maximum possible system performance.
- Steady-state performance analysis assuming nominal system characteristics.

- Transient analysis that predicts system performance beginning from initial conditions and covering an extended time period.

This transient analysis can be altered to model different design alternatives to assist in making design decisions.

The Projects:

Project 1. Natural Circulation Solar Water Heater

The student assignment for this project follows:

Objective:
Design, model, construct and test a small solar water heating system. In this assignment, you will work in teams of three to design a solar water heating system using given materials and meeting specific design constraints. Your design objective is to design and construct a system which will achieve the largest increase in the temperature of the water stored in a given volume container. To meet this objective, you will need to develop an analytical model of your system and modify your design on the basis of your modeling analyses. You will then construct your system and test it under prescribed conditions.

Design Constraints:
You may use only the materials provided or allowed for each team.
The maximum area through which solar energy may be collected is 3 $ft^2$.
No pumps or energy sources other than the sun may be used.
The copper tube provided must be the "solar collector."
Water must circulate from the collector tube to the storage tank.

Materials Provided:
Copper tubing - 3.33 ft long, 0.63" OD, 0.55" ID
Copper sheet - 3 ft x 4", thickness: 0.027"
Large coffee can (to serve as storage tank)
mass = 0.48 lbm empty, will hold 5.30 lbm of water.
Pink foam - 2' x 5' x 1"
Pink foam - 4' x 4' x .25"
Reflective aluminum tape - 2" x 60'
Clear plastic sheet - 4' x 2'
Hose ("Norprene" - 6', 0.50" ID, 0.75" OD
Hose clamps (4)
Solder, glue, fasteners (as needed)
Duct Tape - 1 roll
Plywood - 2' x 4' x .25"
Black Spray Paint

<u>Design Stages:</u>
1. Preliminary design - produce sketch
2. Simple model analysis (assume 100% collection efficiency, neglect water circulation). Determine rate of temperature change and total temperature change in 1 hour.
3. Improve model to include steady state water circulation. Analyze for several assumed conditions. Determine the water mass flow rate with different assumptions regarding mixing in the storage tank.
4. Improve model to include transient conditions, including varying circulation rate, energy storage in circulation loop and heat losses from collector and tank. Identify the most significant loss mechanisms based on your analyses.
5. Improve design based on results of analyses.
6. Construct system.
7. Develop test plant to allow testing of modeling assumptions.
8. Conduct tests and analyze results.
9. Make final design improvements based on tests.
10. Competition.

The analysis for Design Stage 2 requires students to determine the local solar energy intensity on the date of the test, and then determine how fast the water in their storage tank can be heated if all of the solar energy incident in their aperture area goes into heating the water. This analysis gives them an outside estimate of the maximum possible performance of their system, and provides a good reference for comparison with their later transient analysis.

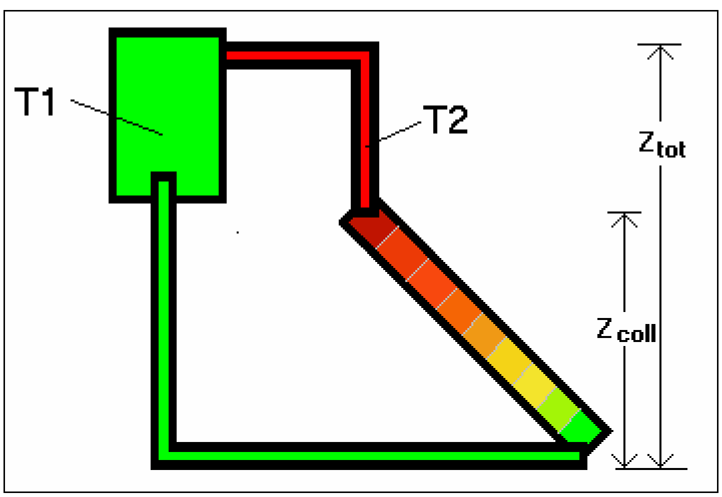

Figure 1. Solar Collector Schematic

The analysis for Design Stage 3 requires students to apply their knowledge of fluid dynamics to determine the natural circulation flow rate. For the system shown in Figure 1, the method for calculating the steady flow rate uses the principle that the head loss from flow equals the pressure difference resulting from density difference between the hot and cold leg.

or: $\Delta P_{hl} = \Delta P_{dd}$

$\Delta P_{dd} = (\rho_{ave\text{-}cold} - \rho_{ave\text{-}hot})\, g\, Z_{tot} = g\{\rho(T_1)Z_{tot} - [(\rho(T_1) + \rho(T_2))Z_{coll}/2 + \rho(T_2)(Z_{tot} - Z_{coll})]\}$

$\Delta P_{hl} = (128\, \mu\, l\, \dot{m})/(\pi\, \rho\, D^4)$ (for laminar flow)[2]

where: $l$ = path length of pipe/tube from tank through the collector

$\dot{m}$ = mass flow rate
D = tube/pipe diameter
$\mu$ = water viscosity
$\rho$ = water (average) density

$I\, A\, \eta_{coll} = \dot{m}\, C(T_2 - T_1)$[3]

where: I = solar energy intensity
A = collector area
$\eta_{coll}$ = collector efficiency
C = heat capacity of water

Given: $T_1$, I, A, $\eta_{coll}$, l, D, $Z_{coll}$, $Z_{tot}$ & C; solve for $\Delta P$, $T_2$ & $\dot{m}$.
Note: To solve these simultaneous equations, it is useful to develop a simple polynomial expansion for $\rho(T)$.

The analysis for Design Stage 3 requires students to perform a "time step" finite difference analysis using a spreadsheet. The model for this analysis is shown in Figure 2.

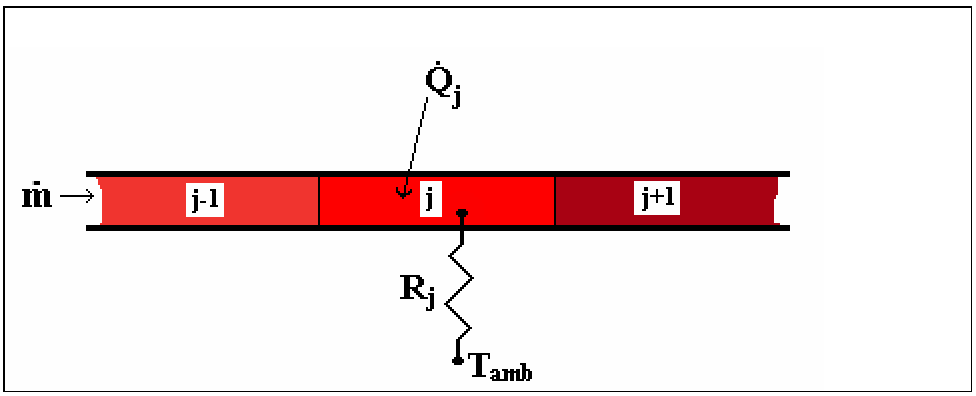


Figure 2. Schematic for Transient Analysis

The transient finite difference analysis uses the following model:

$\Delta T_{i,j} = T_{i+1,j} - T_{i,j} = \{[\dot{m}\, C_w(T_{i,j-1} - T_{i,j}) + Q_j - (T_{i,j} - T_{amb})/R_j]/m_jC_j\}\, \Delta t$

for i = 1 … m; m = no. of time intervals
j = 1 … n ; n = no. of "nodes" in system

$\dot{m} = \Delta P\, \pi\, \rho\, D^4/(128\, \mu\, l)$

$\Delta P = (\rho_{ave\text{-}cold} - \rho_{ave\text{-}hot})\, g\, Z_{tot}$; ($Q_j$ is non-zero only in solar collector)

Students learn that they must be very careful with units, and they must choose a time step small enough to avoid instabilities in the solution. After getting their transient analysis to work, students can alter their design (changing R values or geometric arrangements that will affect the Z values) and determine the effect of their design changes on system performance.

Figure 3 shows a comparison of typical measured vs. calculated temperature values. The measurements were made with a thermocouple located near the bottom of the storage tank. At the end of one hour, the water in the tank was mixed giving a final temperature close to the calculated value. Figure 4 shows the results for the groups of students in one class. The wide range in performance was a reflection of the differing quality of designs (including some systems with leakage problems).

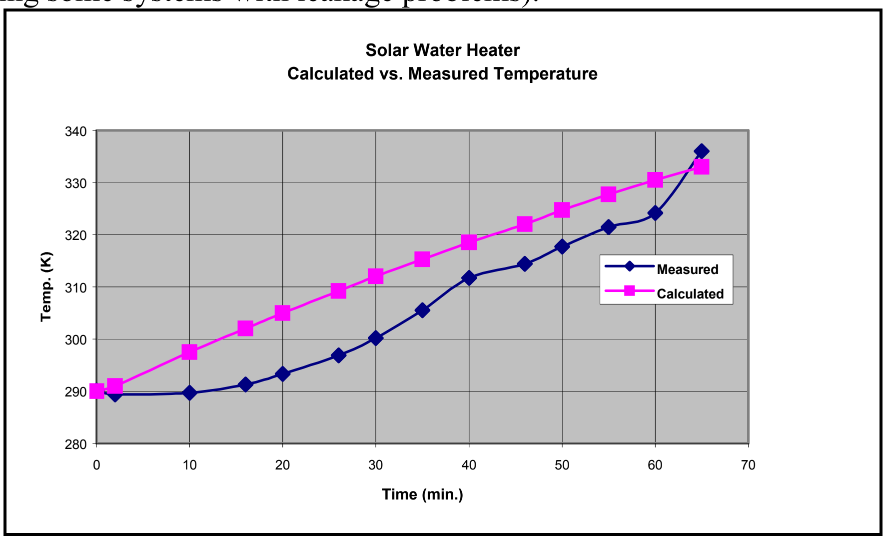


Figure 3. Comparison of Typical Measured and Calculated Temperatures

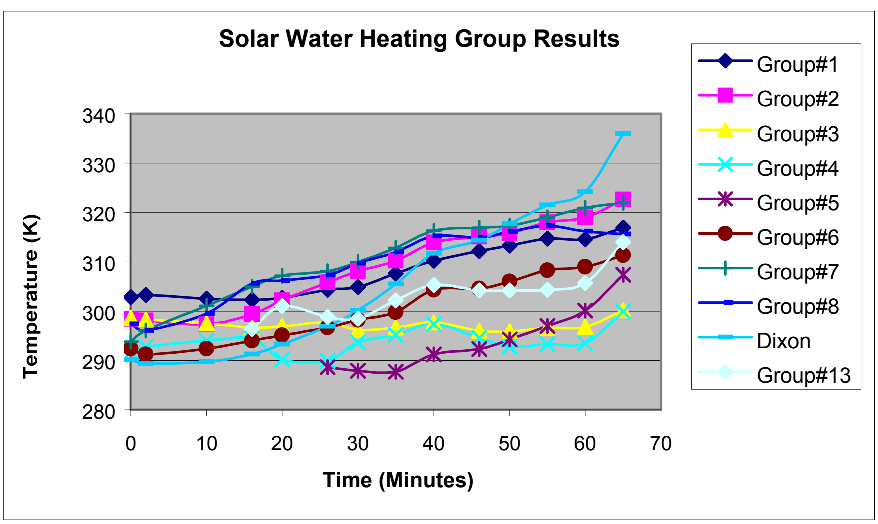


Figure 4. Solar Heating Results for Class

Project 2. Solar Distillation Device

The student assignment for this project follows:

Objective:

Design, model, construct and test a small solar water distillation system. In this assignment, you will work in teams of three to design a solar water distillation system using given materials and meeting specific design constraints. Your design objective is to design and construct a system that will distill the most water during a five-hour period. To meet this objective, you will need to develop an analytical model of your system and modify your design on the basis of your modeling analyses. You will then construct your system and test it under prescribed conditions.

Design Constraints:

You may use only the materials provided or allowed for each team.
The maximum area through which solar energy may enter your system is 4 $ft^2$.
No pumps or energy sources other than the sun may be used.
Your system cannot be moved during the collection period.
You may not add water to your system during the collection period.

Materials Provided:

PVC pipe - 6 ft long, approx. 0.5’’ ID, 0.85’’OD
Heavy Duty Aluminum foil – 18’’ x 8’
Plastic Bottle – You specify size
Pink foam – 2 sheets - 2’ x 5’ x 1”
Pink foam - 2’ x 4’ x .25”
Clear plastic sheet (heat shrinkable) - 4’ x 4’
Surgical Tubing - 4’, 0.50” OD
Solder, glue, fasteners (as needed)
Duct Tape – 1/2 roll
Plywood - 2’ x 4’ x .25”
Black Spray Paint

Design Stages:

Phase I:

1. Preliminary design - Produce sketch of proposed system. Identify which materials are to be used for what purpose.
2. Simple model analysis – Assume all incident radiation during a six hour period in New London in April evaporates water which is condensed and collected. Determine how much water can be distilled according to this “best case” (but unrealistic) model.

Phase II:

1. Perform steady state heat transfer analysis - Assume steady state heat transfer during each of five hours between 10 AM and 3 PM using the model provided in the handout. Determine how much water can be distilled during this five-hour period.

2. Improve system design - On the basis of your analysis results devise a modification of your system, which you think will improve its performance while still meeting the design constraints. Provide a sketch of your revised design. Analyze your modified system for these six one-hour periods to determine how much improvement your modification will produce.

Phase III:

1. Perform transient heat transfer analysis - Do a time-step finite difference heat transfer analysis using a spreadsheet. Determine how much water can be distilled and compare to your results from Phase I and Phase II.
2. Improve system design – On the basis of your transient analysis results devise a modification of your system, which you think will improve its performance while still meeting the design constraints. Provide a sketch of your revised design. Analyze your modified system for these five one-hour periods to determine how much improvement your modification will produce.

The analysis required for phase II uses the equivalent circuit model shown in Figure 5. The incoming solar radiation provides a heat input to the node marked Tw. Heat is transferred through the insulation under the water through the resistance marked Rb. If there were no evaporation, heat would be transferred from the water surface to the plastic cover at temperature, Tp, by radiation and convection. The resistances for these modes are marked Rri and Rci, respectively. The evaporation from the water surface and condensation on the plastic represents the mode of heat transfer that the student seeks to maximize to get the most production of fresh water. This evaporation heat transfer rate is the rate through the resistance, Re. Heat is transferred from the outside of the plastic cover to ambient by convection and radiation. The resistances for these modes are marked Rco and Rro, respectively. To solve for the heat transfer rate through each of the resistances requires a model for each resistance and a solution of the equivalent circuit. The distillation mass flow rate will then be given by: $m_{fw} = Q_e/h_{fg}$, where $Q_e$ is the heat transfer rate through Re. Students are given models for each of the resistances based on the theory of Krieth and Kreider [3]. Since several of the resistances are temperature dependent, an iterative solution is required. This is greatly facilitated by using an equation solver program.

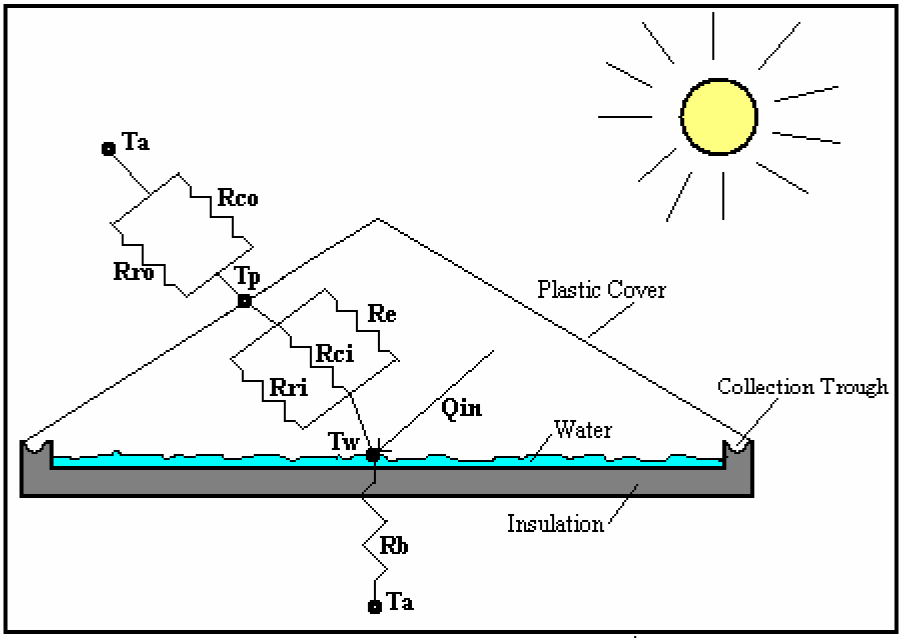


Figure 5. Steady State Model Schematic for Solar Distiller

The transient analysis in phase III requires a finite difference solution of the differential equation:

$$Qin - Qout = m_w C_w dT_w/dt$$

where: $m_w$ = the mass of water in the system
$C_w$ = the heat capacity of the liquid (water)
Qin = the rate of heat transfer into the water from the sun
Qout = the rate of heat transfer out of the water

Since the systems are tested over an extended time period (several hours), the transient solution must take into consideration changes in Qin, $m_w$, and the resistance values that determine Qout. Among the design considerations that students can analyze are:

- The effect of the initial amount of water in the system.
- The effects of using available insulation in different parts of the system.
- The effects of different geometries that will affect the amount of incident energy and the areas from which heat can be transferred to the surroundings.

In addition to these theoretical considerations, students must deal with practical concerns like:

- The method of collecting the distilled water.
- Structural integrity including leak prevention
- Simplicity of set-up and operation

Project 3. Water Heater Using Candle

The student assignment for this project follows:

Objective:

Design, model, construct and test a small water heating system. In this assignment, you will work in teams of three or four to design a water heating system using given materials and meeting specific design constraints. Your design objective is to design and construct a system which will increase the temperature of water in a coffee can as much as possible during a one hour period using the energy provided by the combustion of a given candle. To meet this objective, you will need to develop an analytical model of your system and modify your design on the basis of your modeling analyses. You will then construct your system and test it under prescribed conditions.

Design Constraints:

You may use only the materials provided or allowed for each team.

The only source of energy allowed is the candle provided. (Systems which burn the construction material will be disqualified.)

The water must be heated in a circulation loop external to the can. There can be no heat transfer directly to the can from the flame or air heated by the flame.

No pumps or energy sources other than the candle may be used.

Your system cannot be moved during the heating period.

You may not add to or remove water from your system during the heating period.

The final temperature of the water will be determined by stirring the water in the can after one hour (not before) and then measuring the mixed temperature with a thermocouple.

Materials Provided:

Copper tubing - 4 ft long, 0.25" OD (approx.)

Copper sheet – 4 ft x 2", thickness: 0.01"

Large coffee can (to serve as storage tank) mass = 0.48 lbm empty, will hold 5.30 lbm of water.

Pink foam – 2' x 2' x 1"

Pink foam – 4' x 2' x .375"

Heavy Duty Aluminum foil – 18'' x 4'

Surgical Tubing – 2', 0.375" OD

Hose clamps (4)

Solder, glue, fasteners (as needed)

Duct Tape – 1 roll (shared by 2 teams)

Plywood – 2' x 2' x .25"

Candle – 0.022 kg

Paint

Design Stages:

Phase I:

1. Preliminary design – Produce sketch of proposed system. Identify which materials

are to be used for what purpose.

2. Simple model analysis – Assume all of the thermal energy which can be produced by burning the candle can be transferred to the water in the can. Determine how much the temperature of the water can be increased in one hour (assuming all of the candle will be burned) according to this "best case" (but unrealistic) model.

Phase II:

1. Perform steady state heat transfer and fluid flow analysis – Model system behavior for a range of heat transfer rates to the water in your circulation loop. Estimate the heat transfer rate by doing a heat transfer analysis. Estimate the water circulation rate for different heat transfer rates.
2. Improve system design – On the basis of your analysis results devise a modification of your system which you think will improve its performance while still meeting the design constraints. Provide a sketch of your revised design.

Phase III:

1. Perform a transient heat transfer analysis. Determine the final temperature of the water in the can using this transient model.
2. Improve system design – On the basis of your transient analysis results devise a modification of your system, which you think will improve its performance while still meeting the design constraints. Provide a sketch of your revised design.

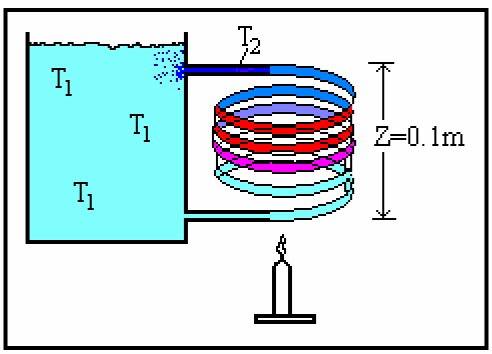


Figure 6. Candle Water Heater Schematic

The analyses required for the three phases of this project are much like those for the solar water heater. The only difference is that there is a different heat source. This project has the advantage of getting students to apply concepts of thermodynamics of combustion. The phase I analysis requires students to determine the maximum possible energy release from burning the candle provided. The phase II analysis requires determination of the natural circulation flow rate for a system like that shown in Figure 6. The phase III analysis requires a finite difference analysis of the system temperature just as with the solar heating system.

While this project has the advantage of getting students to deal with combustion, it has the practical disadvantage of more difficult thermal modeling, combined with the problem of getting a candle to burn completely without melting or burning the construction materials. As a result, the students' ability to make accurate predictions of actual temperature changes was significantly less than with the other two projects.

Student Response:

The response of students to these projects has been quite positive: Some typical comments are represented by those of students who completed the solar distillation project:

- "The solar collector project was the best academic project I have ever participated in. It brought together so much of what I have learned and allowed me to practice real engineering along with creativity, competition and fun."
- "It opened me up to the real world of engineering."
- "It was the most challenging and educationally beneficial assignment of the year."
- "The solar collector project was great. It was a culmination of everything we have been learning thus far. Not only was it fun, but I feel that it really caused me to think on my own and apply basic engineering skills."

Conclusions:

The three projects described provide practical experience in applying basic theory in the design of thermal systems. By giving students experience in building and testing their designs, these projects give students the satisfaction of seeing how theory does, and does not, give them the ability to predict the performance of actual thermal systems.

References:

1: Accrediting Board for Engineering and Technology, *Criteria for Accrediting Engineering Programs*, Baltimore, 2002
2: White, Frank M., *Fluid Mechanics*, 3rd ed., McGraw-Hill, New York, 1994.
3: Kreith and Kreider, *Principles of Solar Engineering*, McGraw-Hill, New York, 1978.

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