AC 2010-175: DESALINATION DESIGN PROJECT FOR THERMODYNAMICS LAB

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Desalination Design Project for Thermodynamics Lab

Abstract

A desalination design project was developed as part of a thermodynamics lab course for junior level engineering students. The principle behind the process is that when salt water is used in an evaporative cooler freshwater vapor is produced leaving the salt behind. By using a heat exchanger the freshwater vapor can be cooled and condensed into liquid freshwater.

The project's main objective was to give student teams first-hand experience incorporating lessons learned in lecture with the practical constraints of designing, building and testing a realistic application. Student teams were given the task of designing a heat exchanger to be attached to an evaporative cooler so as to condense and collect freshwater. This allowed an objective way to compare performance while providing students an opportunity to see multiple solutions to a common problem.

The open-ended project relied heavily on team-based learning and allowed students to be creative while addressing issues during the design phase. A student survey and graded assignment were utilized to assess the resultant student learning. The project culminated in a final report incorporating three main components: Design Analysis, Lab Analysis, and Reflective Analysis.

During this project students were given a first look at topics which will be covered more thoroughly in following engineering courses such as heat transfer and fluid mechanics. Additional benefits of the project included its ability to appeal to a variety of learning styles and exposed the capacity for engineering solutions to be applied in new or alternative ways. The project sought to add everyday relevance to the labs and allowed students to place engineering in a global perspective.

Introduction

Introductory thermodynamics instructors have the difficult task of presenting challenging, and often times dry, material to students in a way that exposes its relevance and excites their interests. One strategy for bringing the thermal/fluid sciences to life for the students is via hand-on projects in which students design, build and test (DBT) a product[1, 2, 3, 4]. DBT projects present a valuable opportunity to learn about the obstacles and compromises engineers address when working to make an idea a reality during the design and build phases. The testing phase supplies concrete feedback on how well a design works and generates discussion on any errors in judgment during the design process and how one might improve on the design.

An additional strategy is to show students how thermodynamics ties in with inventive solutions for meaningful problems. The idea for the current project was inspired by a program on the Discovery Channel titled: *Building the Future: The Quest for Water*[5] which discussed an idea for an innovative full scale desalination plant called the Teatro del Agua. The mechanism of operation is "a series of evaporators and condensers such that the airborne moisture from the evaporators is then collected from the condensers, which are cooled by deep seawater[6]." In fact, desalination of seawater is not a new technology and it is believed that ancient Greek sailors used simple evaporative technologies to purify water[7]. The American Water Works Association forecasts that the world market for desalinated water will grow by more than $70 billion in the next 20 years[7], making this an important topic for coastal population growth nationally and internationally. Condensers and evaporators are components that are commonly used in thermodynamic systems and can be analyzed from a thermodynamic standpoint.

In this paper we discuss the development of a desalination DBT project as part of an introductory thermodynamics course for junior level engineers including the implementation, project assessments, and lessons learned.

Project Description

A pre-project survey, found in Appendix A and based off a survey by Coronella[8], was used to assess the students' perceived abilities in multiple areas in order to allocate skills evenly amongst the groups and avoid scheduling conflicts. Four teams were assigned to one of two evaporative coolers and given the task of creating a heat exchanger which could be attached to the outlet of the evaporative cooler with the goal of condensing and collecting the water vapor. The key issues to be addressed included creating a device through which cold water would be circulated and would permit maximum heat transfer between the air and water, designing a method for directing the moist air over the heat exchanger, implementing a method for collecting condensed water, and avoiding leaks. To expose students to different heat exchanger designs and applications they were all asked to research a commercially available heat exchanger including the material it was made of, the fluids between which heat was exchanged, nominal operating temperatures, application and a picture or schematic of the unit. All results were then presented to the class.

The key learning objectives for the project included:
-how to manage a project
-how to find and use outside information to help drive a design
-how to communicate succinctly your progress and achievements
-understanding the importance of psychrometrics in cooling units
-understanding the implications involved in converting salt water into freshwater

With the goal of encouraging creativity the performance of each design was minimally weighted in the grading and the design aspect was completely open-ended. The instructor was available for questions and to help recognize potential issues but refrained from offering suggestions during the design phase. As heat transfer or fluid mechanics courses typically follow thermodynamics the project was not intended to be a capstone, but did provide valuable experience from which a student could build from in a future senior design project. The project also provided an opportunity to present a qualitative introduction to aspects of internal and external fluid flows as well as the different forms of heat transfer and how they occur. Some of the final products can be seen in Figure 1.

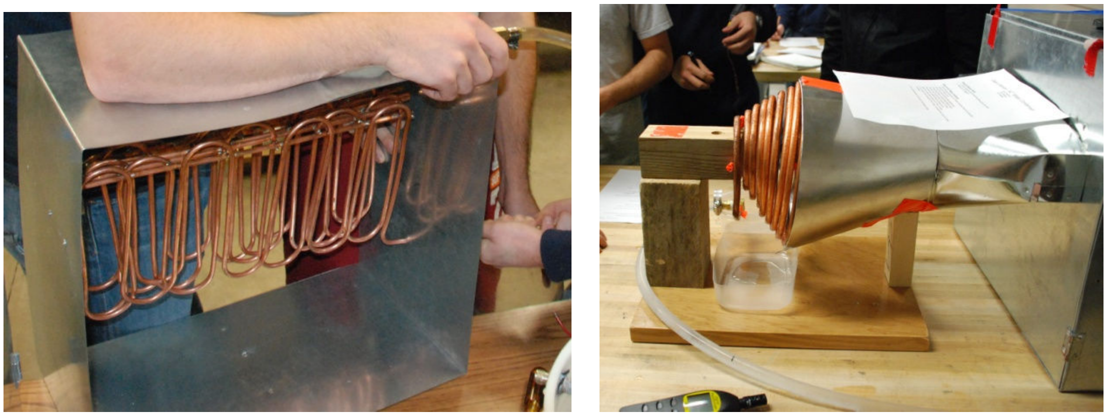

Figure 1. Heat exchanger designs

Upon completion, the desalinators were used in a lab utilizing the first law of thermodynamics and psychrometrics (Appendix B). During the lab student designed heat exchangers were attached to an evaporative cooler which was running with saltwater as opposed to freshwater. In the evaporative cooler air is blown through a membrane which was wetted with the saltwater causing water vapor to evaporate and the air temperature to decrease. This moist air then traveled over a heat exchanger through which cold water was circulating as shown in Figure 2.

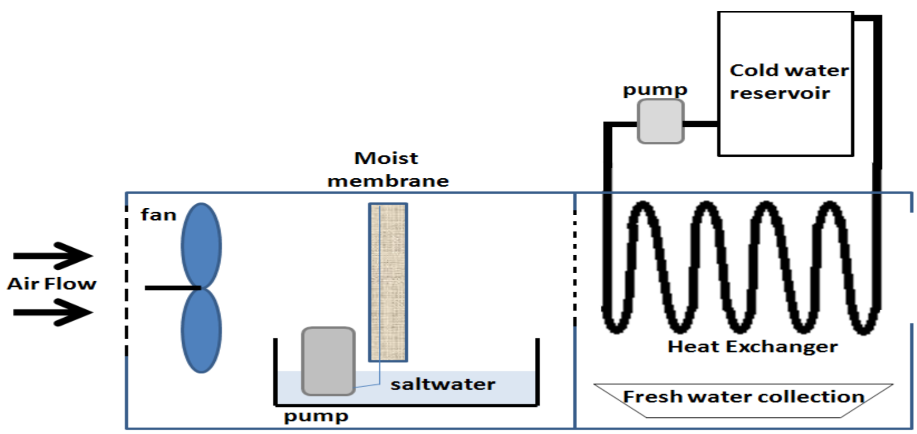

Figure 2. Schematic of lab set-up

To gather data students recorded the temperature, relative humidity, and flow rates at various locations throughout the system. Power consumed by the pumps and fans was measured with an electricity load meter (P3 Kill-A-Watt) and a refractometer (National Industrial Supply) was used to measure the salinity of the water in the evaporative cooler and the condensed water. The goal of the lab was to allow students to see how the temperature of air can be lowered through water evaporation, give students experience working with the equations and chart involved in a psychrometric analysis, test their designs and see the other designs. Each team worked with another team's desalinator and reviewed their design. To facilitate the operation by other teams and to force students to think critically about simplifying their design, teams created user manuals with instructions on how to properly and safely use their desalinator.

A final report synthesized the different components of the project with three main sections: Design Analysis, Lab Analysis, and Reflective Analysis. For the Design Analysis teams discussed the main problems their design addressed, alternative designs considered, compromises made, initial testing problems and solutions, and any other relevant information that was considered. Also included in this section were the bill of materials for the project, Solid Works drawings of their design and the user manual. The Lab Analysis section included the data collected while testing as well as the thermodynamic analyses and calculations asked for in the lab handout (Appendix B). For the Reflective Analysis section teams were asked to reflect on the process of designing and testing their desalinator and suggest possible improvements to their design. In this section students further discussed the practicality of widespread condensed vapor desalinator use including a brief comparison to other technologies and global regions which could benefit.

Representative Results

Table 1 shows a comparison of the performance of the four different designs. Two of these designs were tested on evaporative cooler #1 while the other two designs were tested on evaporative cooler #2. By having two heat exchanger designs tested for each evaporative cooler there is clear evidence that different design choices produce significantly different results. By having the students calculate the cost to operate the desalinators it is seen that for the simple designs used it would cost from $0.42-$1.36 in electricity to produce a gallon of condensed water. Compared to the price of bottled water the process seems viable, though the costs are much higher than that of currently used technology such as reverse osmosis which has costs of roughly $0.002-$0.025 per gallon[9] but requires more complex equipment. These results also clearly show that roughly 15% of the salt remains in the condensed water indicating that further improvements are needed to produce freshwater. This result is likely due to the air flow not only evaporating water vapor, but also carrying small droplets of saltwater off the membrane. A thicker membrane or lower air flow rate could potentially reduce this issue.

Table 1. Performance comparison of designs

	Cooler # 1		Cooler # 2	
	Team 1	Team 2	Team 3	Team 4
Heat Exchanger Effective Efficiency (%)	12.4	7.2	4.8	13.7
Rate of Water Condensation (mL/min)	1.37	0.58	1.54	1
Energy Cost for Condensation ($/gallon)	0.6	1.36	0.42	0.64
Initial Salinity (ppt)	40	40	40	40
Final Salinity (ppt)	5	6	5	6

Table 1 also shows the surprising result for the designs tested on evaporative cooler #2 that the less efficient heat exchanger (Team 3) condensed water at a higher rate. This result is likely due to measurement errors. To avoid these errors in the future it would be beneficial to have multiple groups independently take data and compare the measurements as a class. Had time permitted, this lab could have also been used to introduce aspects of uncertainty analysis including types of uncertainty, how measurement uncertainties are combined, and their propagation to determine a final uncertainty. Doing so would provide an opportunity to discuss the importance of careful measurements and reasons why measurements might not agree.

At the completion of the project the class examined the different designs while discussing the pros and cons of each and brainstorming ideas for potential improvements. Many of these ideas were reiterated in the reflective analyses where students acknowledged that increasing heat exchanger surface area and giving greater consideration to empty space and air flow through the exchanger would improve design. Additional concerns involved air and water leakage as many students learned the importance of Teflon tape. The reflective analysis further exposed the students' understanding that while the final products were not very efficient there would be great potential for this technology if gains could be made. Students noted the simplicity in design with only a few simple moving parts, the lack of hazardous/dangerous materials, and the ease of operation as a major advantage to this type of desalination process. Because of these traits, the amount of personnel, training, maintenance, and tools needed for operation would be minimal making its use in disadvantaged locations viable once the energy costs were reduced. Students further noted that potential for widespread use would also benefit small island nations, the Middle East where almost 75% of global desalination occurs[10], and even in the states of California and Florida. Interestingly, none of the groups commented on the negative aspects of using saltwater in a heat exchanger as proposed for the Teatro del Agua, such as corrosion and fouling issues which can lead to diminished performance and part life or require more expensive materials and/or maintenance. While these issues were absent in this short duration lab they would be salient to widespread adaptation of this technology.

Project Assessment

The project was assessed via two methods: subjective feedback was taken using a post project survey (Appendix C); objective feedback was taken by subject specific questions on the final exam for the course (Appendix D). Half of the class participated in the desalination project allowing the other half to be considered a control group. This control group did not use the desalinators but did participate in a very similar psychrometric analysis and an experiment using evaporative coolers. Table 2 demonstrates that from the students' viewpoint the project was successful in many of its aims. The group aspect of the project and the open-ended structure were particularly highly rated.

Table 2. Design project survey results

Statement rated from 1-5 (1=strongly disagree, 5= strongly agree)	**average**
The design project helped me to strengthen my understanding of material presented in lecture.	4.00
The design project helped me to better understand the practical constraints and compromises that exist in engineering projects.	4.15
I prefer the open-ended structure of the design project to one with a more rigid structure.	4.15

Group based projects are an effective tool for improving engineering skills.	4.54
My learning was improved by having multiple groups design for the same problem.	3.92
I understand the concepts of relative humidity, wet bulb temperature and dew point.	3.77
The design project sparked my interest to learn more about the thermal/fluid sciences.	3.54

A few key points can be summarized from the answers to the open-ended questions at the end of the survey.

Students would have liked: an opportunity to test the design earlier, some initial design examples to start from, more money and time for the design and build phase (they had a $30 per student budget and 7.5 hours of class time), more time testing their actual design as opposed to third party testing, reduced math for the lab analysis.

Students realized they could have gotten more out of the project if they had: spent more time on it, researched and considered more potential designs, done more testing early on to allow for improvements.

Students felt the best parts were: the hands on building, testing their design, freedom in design, the relevance of the designed product, seeing their final product work.

To determine if the design aspect of the project had an effect on student learning of psychrometrics the desalinator design student responses to the objective feedback questions were compared to the control group using an unpaired two-sample t-test with equal variances (as verified by an F-test with $P = 0.48$). The results in Table 3 indicate that the difference in mean performance on psychrometric questions on the final exam between the groups was not statistically significant (i.e. $P > 0.05$). The desalinator design group answered 60% of the psychrometric questions (Appendix D) correctly and the control group 61.8%.

Table 3. Statistical analysis results of performance on psychrometric exam questions

	Desalinator Design Group	Control Group
Mean	0.600	0.618
# of students	13	11
two-tailed P-value	0.84	

It is noteworthy that the two groups rated themselves different in terms of comfort with psychrometrics (question 7, Appendix C). The average control group response to this question was 4.27 as compared to 3.77 for the desalinator design group (two-sample t-test $P = 0.04$). This result shows the importance of including graded assessments in addition to student surveys as a means of gathering unbiased feedback of student learning.

Lessons Learned

Many valuable lessons were learned during this first trial with a condensed vapor desalination design project. In the future it would be beneficial to schedule the project to allow multiple tests. This would permit students to iteratively improve their design and learn more from their mistakes. The project could be simplified by perhaps removing the third party testing, user manual, and Solid Works portions to allow greater focus on the design and testing. Also, this could be facilitated by improving student access to the materials outside of lab or by simply scheduling more days of testing.

The feedback reveals that understanding of psychrometrics was not enhanced by the project structure when compared to a control group. One possible reason for this is that each team turned in a single report where one could imagine a single group member performing the necessary lab analysis in which the students would be forced to work with the psychrometric equations. To ensure that all students had exposure to the analysis it may have been more productive to require each student to individually hand in a lab analysis, as well as having it as part of the final report. Additionally, another variable could be included in the testing and/or analysis such as the temperature of the water in the evaporative cooler (warm vs. cold) or the temperature of the air being blown through the evaporative cooler (warm vs. ambient). Seeing the effect of another variable could increase conceptual understanding while its inclusion in the analysis would give greater exposure to the math involved.

Finally, it seemed that there was little variety in the designs with students relying on left over copper tubing in the lab as opposed to locating their own materials and understanding the compromises made when picking materials. Though one can understand the motivation for using material that is on hand it may detract from the process of designing a product. As none of the teams came close to using the full amount of their budget it was not necessary to rely on free materials. As opposed to simply determining the energy costs to run the desalinator, students could also have factored in the cost to build the desalinator. A more accurate picture of all the costs involved could have been accounted for in a more thorough Bill of Materials.

Conclusion

An open ended desalination design project was created for use in an introductory thermodynamics laboratory on psychrometrics. The project was built from an innovative concept that lent itself to thermodynamic analysis and exposed students to the connection between classroom material and real-world applications. Results from the project show that the process of producing freshwater by evaporating saltwater and condensing the vapor requires greater care than one might initially expect as only 85% of the salt was removed. A student survey and subject specific questions on the final showed the project to be successful in many of its aims with the group aspect and design freedom having the greatest positive response.

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Appendix A : Pre-Project Survey

Name	
e-mail address	
Major	
Do you live on campus or off campus?	
Best times to meet outside of class	
Is there any student you cannot work with?	
Rate your skills in the following areas from 1-10 :	
Handiness (mechanical abilities with tools)	
Math	
Computers	
Writing	
Leadership (managing a team)	

Appendix B : Lab Description

Psychrometric Lab with Desalination

In this lab an evaporative cooler will be evaluated utilizing 1st Law principles and psychrometrics.

Steps:

1. Measure the salinity of the water to be used in your evaporative cooler.
2. Fill the water reservoir in your evaporative cooler and turn system on.
3. Allow system to reach steady state conditions (~5 minutes).
4. Record data.
5. Let system run (note the time) while collecting condensed water.

Analysis:

a). Sketch the basic operation of your unit. Put in arrows for mass and energy flow.

b). Record the following data (remember units):

Evaporative Cooler	
Initial salinity	
Ambient Temp	
Ambient RH	
Cooler Outlet Temp	
Cooler Outlet RH	
Cooler Power consumption	
Air flow rate	
Ht. Exch. Air Outlet Temp	
Ht. Exch. Air Outlet RH	
Ht. Exch. flow rate	
Ht. Exch. Power consumption	
Ht. Exch. water inlet Temp	
Ht. Exch. water outlet Temp	
Condensed water salinity	
Amount of condensed water	
Run time	

c). Plot the ambient conditions, evaporative cooler outlet conditions and heat exchanger outlet conditions on a psychrometric chart.

d). Calculate the rate at which water vapor is being evaporated from the moist membrane.

e). What is your evaporative cooler's effective efficiency?

f). Assuming the effective efficiency of your cooler is constant, what would the air outlet temperature be for current conditions in New Orleans and Phoenix? Include these conditions on the psychrometric chart.

g). What is the effective efficiency of your heat exchanger?

h). How much heat is being removed from the moist air by the heat exchanger?

i.) How much would it cost to operate the set-up long enough to condense 1 gallon of water?

Assessment of other teams heat exchanger:

Third party testing and assessment is a part of your grade and each group will have a chance to hook up and use another heat exchanger. Peer feedback will be completely confidential, though a summary of the results may be presented.

Peer Review of Performance

Please rate the heat exchanger and user manual made by the other teams using this form.

Reviewer:

Team being reviewed:

Criteria	**scale of 1-10 (10 being highest)**
User manual is clear	
User manual is concise	
Ease of implementation with evaporative cooler	
Ease of collected water retrieval	
Perceived sturdiness of heat exchanger	
Lack of air leakage	
Lack of safety issues	

Any additional notes or feedback:

Team being reviewed:

Criteria	**scale of 1-10 (10 being highest)**
User manual is clear	
User manual is concise	
Ease of implementation with evaporative cooler	
Ease of collected water retrieval	
Perceived sturdiness of heat exchanger	
Lack of air leakage	
Lack of safety issues	

Any additional notes or feedback:

Appendix C : Assessment Survey and Questions

Design Project Survey

1. The design project helped me to strengthen my understanding of material presented in lecture.

strongly disagree	disagree	neutral	agree	strongly agree
1	**2**	**3**	**4**	**5**

2. The design project helped me to better understand the practical constraints and compromises that exist in engineering projects.

strongly disagree	disagree	neutral	agree	strongly agree
1	**2**	**3**	**4**	**5**

3. I prefer the open-ended structure of the design project to one with a more rigid structure.

strongly disagree	disagree	neutral	agree	strongly agree
1	**2**	**3**	**4**	**5**

4. Group based projects are an effective tool for improving engineering skills.

strongly disagree	disagree	neutral	agree	strongly agree
1	**2**	**3**	**4**	**5**

5. My learning was improved by having multiple groups design for the same problem.

strongly disagree	disagree	neutral	agree	strongly agree
1	**2**	**3**	**4**	**5**

6. I understand the concepts of relative humidity, wet bulb temperature and dew point.

strongly disagree	disagree	neutral	agree	strongly agree
1	**2**	**3**	**4**	**5**

7. The design project sparked my interest to learn more about the thermal/fluid sciences.

strongly disagree	disagree	neutral	agree	strongly agree
1	**2**	**3**	**4**	**5**

What could I have done as a student to get more out of the project?

What was the worst part of the design project?

What was the best part of the design project?

Appendix D : Objective Assessment Questions

1. On the psychrometric chart, a constant pressure cooling process appears as a line that is:

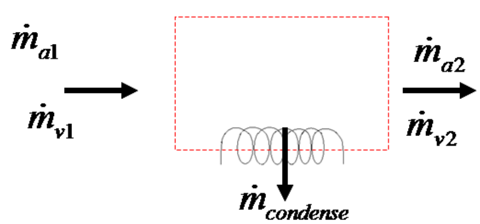
   a) horizontal to the left
   b) horizontal to the right
   c) vertical downward
   d) diagonal upwards to the left (NW direction)
   e) curving downward to the left (SW direction)

2. An air stream at a specified temperature and relative humidity undergoes evaporative cooling by spraying water into it at about the same temperature. The lowest temperature the air stream can be cooled to is:

   a) the dry bulb temperature at the given state
   b) the wet bulb temperature at the given state
   c) the dew point temperature at the given state
   d) the triple point temperature of water
   e) the atmospheric temperature at the given state

For #3-5:

Atmospheric air at 25 ^{o}C and humidity ratio of 4 g/kg dry air is cooled and dehumidified as it flows over the coils of a heat exchanger to 20 ^{o}C and a relative humidity of 10%. If the mass flow rate of dry air is 0.7 kg/s, determine the rate at which water is condensing on the heat exchanger for steady conditions.



3. The enthalpy per kg of dry air entering the dehumidifier is most nearly:

a) 50 kJ/kg dry air | b) 25 kJ/kg dry air | c) 78.5 kJ/kg dry air
d) 35 kJ/kg dry air | e) 15 kJ/kg dry air

4. The mass flow rate of water condensing in kg/s is:

a) 1.1 b) 0.01 c) 0.007 d) 0.44 e) 0.00175

5. The heat transfer from the incoming air stream to the coils of the dehumidifier in kJ/kg dry air is:

a) 10.8 kJ/kg dry air | b) 48.0 kJ/kg dry air | c) 75.5 kJ/kg dry air
d) 48.6 kJ/kg dry air | e) 60.7 kJ/kg dry air