AC 2010-1608: POSTER: ENGAGING K-12 STUDENTS IN ENGINEERING DESIGN OF COOLING SYSTEMS FOR ELECTRONICS

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Abstract

Successful lessons in the K-12 mathematics and science classroom incorporate hands-on testing, creative design, and relevance to real life. Consider the notorious question asked by a student to a teacher: "*When am I ever going to use this?*" Because students are naturally inquisitive, everyone benefits when we constructively use this trait in the learning environment and help students to answer their own questions. The purpose of this paper is to describe a lesson that engages high school mathematics and science students in an interactive relevant engineering design problem.

As part of the CREAM (Culturally Relevant Engineering Applications in Mathematics) program at Washington State University, graduate students developed a lesson that reveals science and mathematics principles used to address energy dissipation problems important in our technology-based world. The dissipation of heat generated by electronic components has become a major challenge as technology becomes increasingly compact. Systems require solutions beyond air cooling. Top performance requires liquid cooling and optimizing the liquid-solid interactions that remove heat from surfaces of electronic components. In research, combining a mechanically roughened surface with a molecularly applied surface coating and an efficient liquid, heat removal can be significantly increased.

A three-day lesson was developed to provide a series of activities where students could explore material properties, liquid-solid interactions, heat dissipation, and responsible engineering design. The activities advance students from being observers to being innovators as they grow their understanding of material properties and engineering design. The goal was to allow students, through the classroom experiences, to validate that design improvements can increase heat dissipation. Students learn that carefully engineered modifications result in smaller, cheaper, and more reliable personal electronics. They also see that understanding the concept of surface coating has additional relevant applications.

The lesson begins by posing the question: "*Can a liquid be stacked on a flat surface that has no edges?*" To explore this question, students use rulers, pipettes, and electronic balances to quantify the amount of a liquid that can be stacked on a flat surface. From data collected, students determine areas, masses, and volumes, and they generate a series of bar and scatter plots to describe their results. Students are given opportunities to discuss observed and inferred differences among the different liquids and surfaces to identify and deepen understanding of surface tension principles exhibited by their experiments. On the third day, students are challenged to create their own custom liquid-solid design that will hold the most fluid for the least cost. They apply the data they collected and discussions from the previous two days to guide their design. From this series of activities, students learn about fluid properties, liquid-solid interactions, and cost versus performance design choices.

This paper describes a current engineering problem, provides details of the activities, and presents evidence for impacts on high school students. Students' attitudes about mathematics and science are revealed, as are their confidence related to doing mathematics and science. Data also

shows what students enjoyed, learned, and/or would change after participating in the lesson. A full lesson plan, activity description, and implementation instructions, with lesson worksheets are available upon request.

Introduction

The CREAM (Culturally Relevant Engineering Applications in Mathematics) program was created at Washington State University (WSU) in 2006 under National Science funding (DGE 0538652). The program uses culturally-relevant engineering applications in mathematics to energize graduate students, high school teachers and students, and university faculty to reform mathematics and science education and heighten engineering career aspirations.

Teachers with WSU graduate student mentors facilitate pedagogically sound, student-centered, engineering projects in which high school students create engineering solutions to local socially-important problems while achieving classroom objectives and state mathematics and science standards. Diverse and geographically-distant students and teachers are connected to form learning communities to improve teaching, learning, and understanding of engineering.

Technology Background

As the power of electronic devices has increased, so has the need for improved heat removal. Such applications that require the use of high heat flux (heat transfer rate) electronics include: high power lasers, aviation, and national security/military industries. To the consumer this will result in smaller, cheaper, more reliable, and faster personal electronics.

This need for greater heat transfer is exemplified by the switch to immersing the CPU of the Cray-2 supercomputer in a liquid bath. With required heat fluxes now approaching $1kW/cm^2$, renewed attention is being given to novel thermal management systems. It is known that the highest heat transfer coefficients can be achieved through vaporization. Thus, companies have focused on cooling systems that incorporate the phase change of a liquid to a vapor as the primary means of removing heat from electronics. Other researchers have turned their attention to changes in design of the heated surface. The purpose of these surface modifications is to increase surface area, enhance boiling phenomena, and/or improve surface wettability. In either scenario, the thermal performance of these systems depends on understanding and optimizing the liquid-solid interactions, specifically interfacial tension. However, more research is needed to define this optimum liquid-solid interaction.

Creating efficient heat transfer surface designs should consider the following design requirements:

- Fluid must be compatible (or safe) for electronics and all other system components.
- Fluid must not be hazardous to the environment or human health.
- Fluid must be a liquid at standard temperature and pressure.
- Material cost and weight must enable solutions to be profitable in industrial settings.
- Capability of a heat dissipation rate of at least $500W/cm^2$.

The same principles associated with the liquid-solid interactions in heat transfer are also relevant to a variety of other applications, including inkjet printer technology, glue adhesion, design of self cleaning surfaces and water repellent technology. The focus of the classroom lesson is an application associated with the principal author's research topic: two-phase direct liquid-surface cooling of electronics. The relevant research goal is to design a technology capable of increasing the rate of heat removal from electronic components. This technology combines the use of an augmented surface structure and a custom designed fluid to improve liquid-solid interactions and thus heat transfer over traditional technologies.

To provide a design scheme of one solution currently being investigated, Figure 1 depicts a traditional copper substrate that might traditionally be used to dissipate heat from an electronic component. The substrate surface is then augmented with micro-machining to produce a matrix of micron sized posts. Finally, these posts can be chemically augmented to further improve their interaction with the fluid of choice.

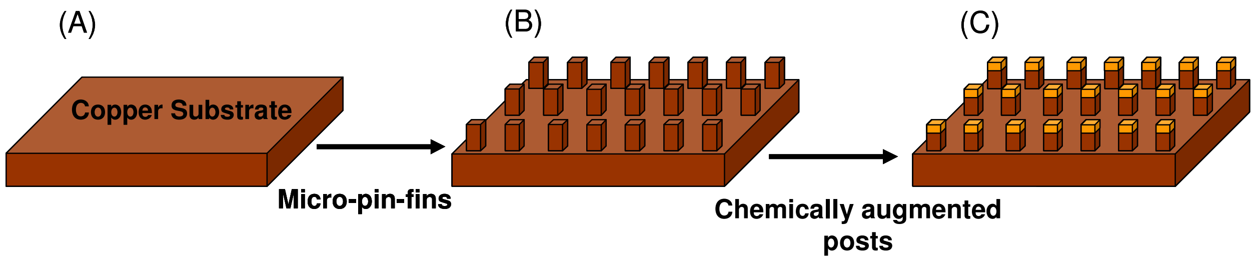

Figure 1: Schematic of a (A) traditional copper substrate heat sink, (B) substrate with micro-pin-fins machined into surface, and (C) final augmented design with chemically enhanced posts.

The surface enhancement is one part of the optimized design solution. The second part is to identify a fluid that shows the maximum potential for heat removal. This potential, typically referred to as CHF (or critical heat flux) is a function of numerous fluid properties. The author's research is looking to identify a fluid mixture (composed of two liquids) that exhibits the greatest CHF. However, the fluid choice must also satisfy the above design requirements. Figure 2 demonstrates how the CHF curve may appear for a particular combination of liquids. Below the predicted CHF curve, or maximum amount of heat removal possible, can follow numerous paths depending on the individual fluid properties (latent heat, viscosity, density, surface tension, etc). The goal is to determine the point at which a maximum CHF occurs, in this case between a mole fraction of 0.1 and 0.2.

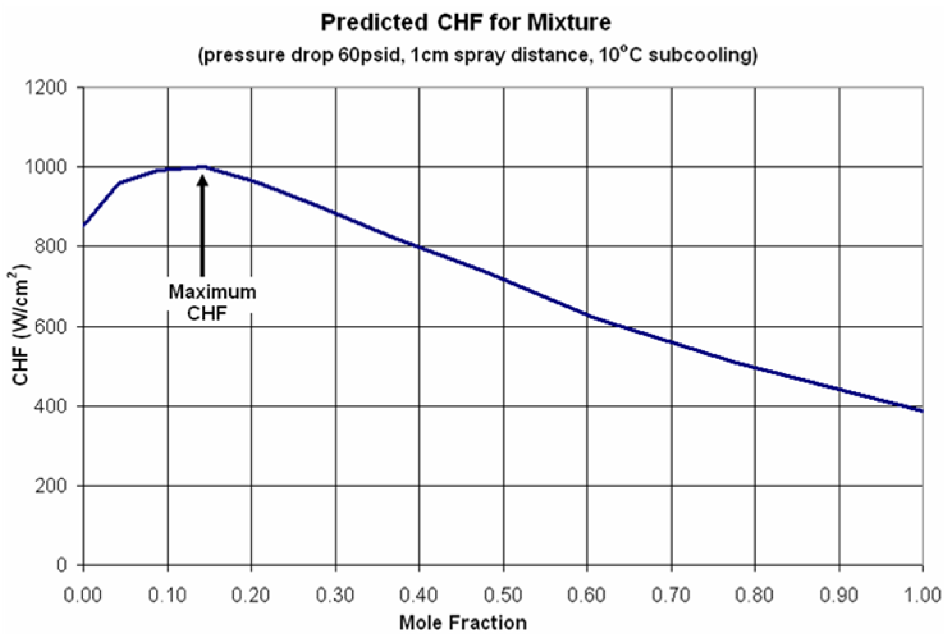

Figure 2: Predicted Critical Heat Flux possible by a two-liquid mixture.

Lesson Introduction

This instructional lesson is primarily composed of two activities. The first provides students an opportunity to practice a testing procedure and record data as they vary two variables: fluid type and surface material. The second activity gives students the opportunity to apply information they obtained in the first activity to create a liquid-solid combination that achieves the design requirements. Possible solutions can be created by changing the (1) liquid choices, (2) surface material choices, and (3) the solution objective (for example: the most liquid by volume, the least liquid by volume, the most drops, or the fewest drops).

This lesson has been implemented over two school years to high school (9-12 grade) students in a broad range of mathematics and science classes that include: 9^{th} grade integrated science, biology, chemistry, forensics, pre-calculus, integrated math class (that merges learning of algebra, geometry, and pre-calculus together), and a lab math class that provides students a second math class during the day if they are considered significantly behind in their math curriculum. The first year the lesson was implemented into five classes composed of 96 students, and in the second year the lesson was implemented into 10 classes composed of 200 students. In order to achieve different curricular goals for the math and science classes, the activities were adapted while maintaining similar test procedures and the overall objective of the lesson.

The activities described below were used in the classes as a three day consecutive activity. These activities were used in all of the math and science classes, although questions in the classes varied to meet class objectives. Students in the classes come from a low socioeconomic status where their highest education level is high school.

Day 1. Experimental Methods and Data Collection

The first day begins with an introduction and discussion of how scientists or engineers might approach a problem. Important points include:

- the purpose, or why are they investigating the problem in the first place
- variables involved in the problem
- outcomes, or what you are trying to learn or determine
- how to create a hypothesis
- how to test a hypothesis
- what criteria will to use to know if a hypothesis is correct or to know a solution is found to the problem

In this activity, the students begin by determining if a column of liquid can sit on a flat surface with no walls to contain the liquid. Next they investigate if changing the surface material makes a difference, and if changing the liquid will make a difference in liquid containment. The first connection to engineering is in the importance of material selection when an engineer is designing a product. Key points to consider in material selection are the following:

- Purpose – what is the product (solid and liquid) going to be used for?
- Consumer - who is going to use the product?
- Lifetime and Durability - how long is it expected to last?
- Compatibility – what other materials will the product contact; will the product react adversely to anything it could contact?
- Physical Properties – what are the necessary physical characteristics of the product (high melting point, low weight, high strength, or high flexibility)?
- Cost – what is a reasonable cost for the consumer: initial purchase costs, upkeep, disposal, etc

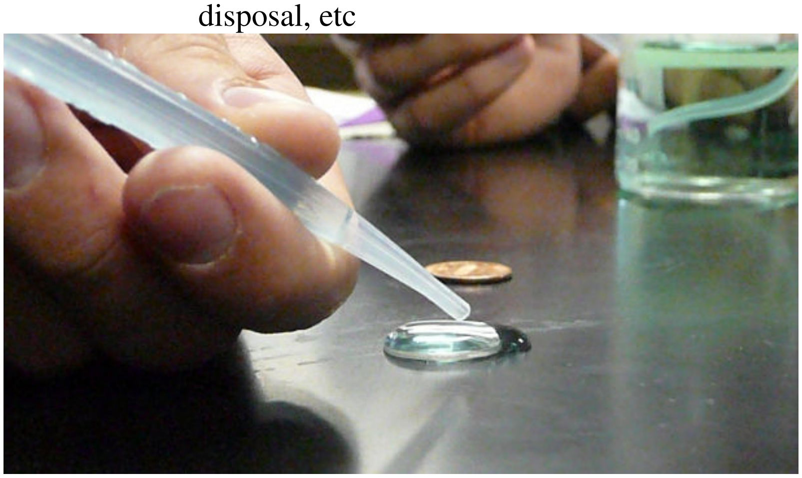

Figure 3: Students testing set of liquids on a plastic penny and copper penny surface.

By the end of the first day, the following learning should be achieved:

(a) Writing Hypothesis - students will demonstrate that they can write a hypothesis using the correct form and accurately reflecting the question being posed

(b) Following Procedures - students will identify the materials needed for each activity and use these materials to complete the step as directed.

(c) Collecting Data - students will be able to gather data accurately, describe the data they obtained, and explain how they collected the data.

Table 1: Day 1 Learning Outcomes

Learning Outcome	**Evidence Sought**	**# Students Successful**
Writing Hypothesis	Students use the correct form (if…then…because) to phrase their hypothesis and the hypothesis answers the question being posed.	290
Following Procedures	Students are able to read and take correct actions described in procedures. They can follow steps in the order presented. Students are on task, quickly following the directions given, and asking questions when clarification is required. Students are able to suggest and describe procedural changes to make testing more efficient, to eliminate errors due to interpretation, etc.	285
Collecting Data	Students are accurately recording data they collect; they recognize whether or not the data is leading them towards validating or disproving any of their hypotheses.	280

Implementation of the first day's activities in a variety of class settings produced the following types of responses. At the start of the lesson students were very vocal about their predictions that it would be impossible to stack a liquid on a flat surface. In general, they based these predictions on observations of liquid-solid interactions in their day-to-day lives. One student misconception that repeated itself through the majority of classes was that if it was possible to stack liquid on flat surfaces then water would not bead up and roll off of cars when the car was freshly waxed. Many students supposed that a liquid would eventually soak into a surface like when it rained and the concrete sidewalks soaked up the water. Initially, the majority of students were disinterested in the activity because they felt they already knew the outcome. It took only long enough for the first few groups to begin testing before there was a buzz throughout the classroom as students compared results amongst themselves. Students took it on their own to begin competing to see who got the most drops on a particular surface. What was interesting was that while they were challenging each other, they were questioning exactly how a group conducted their test. This open discussion allowed students to see the varied interpretations possible in the procedures that had been provided. Some specific observations of student learning include the following:

- Students were surprised when they determined that pennies could hold a measurable height of liquid
- Students could describe that the size of their droplets would change depending on the speed of discharge and on the liquid they were testing
- Students could explain why it was important for them to repeat measurements and take an average value
- Students could describe the general trend that one surface consistently held more drops
- Students could describe their observations of how drops reacted with the existing liquid column during different times in the test
- Students could show how to read the scale on the ruler when performing height and diameter measurements on the penny surface

Day 2. Data Analysis and Discussion

During the second day, students continue to collect data on the liquid-solid interactions being observed. The majority of the day, though, is spent analyzing their data to make sense of what they found. Their data on the number of drops held on the surface in each case and the height of the liquid column are used to then calculate the volume of liquid held on each surface. Students are then asked to critically think about how they could confirm their volume calculations and to create bar graphs and trend lines that describe the results. Students record their data on the board to share with the rest of the class. In addition, students are led in a discussion of engineering design: its role in engineering, methods used, and challenges. The class is given an opportunity to ask questions regarding the properties of materials available for them to use for surface modification. This information will help them to make decisions during day three when they will be creating their own liquid-solid combination.

By the end of day 2, the following learning should be achieved:
(a) Interactions- students are able to describe how the three fluids interacted differently (or similarly) with the two solid surfaces.
(b) Liquid Characteristics - students are able to explain the basic differences in properties of the three liquids.
(c) Solid Characteristics - students are able to describe observable differences in the two surfaces.

Table 2: Day 2 Learning Outcomes

Learning Outcome	Evidence Sought	# Students Successful
Interactions	Students can describe how each liquid behaved in contact with each solid, referencing concepts of surface tension. Students can describe trends (or similarities) that they observed. Students can describe the differences in the shape of the liquid column, and make reasoned guesses about the causes of these differences.	222
Liquid Characteristics	Students can describe characteristics of liquids that can be used to identify liquids that are different or the same (appearance, texture, color, etc). Students can recall prior knowledge about how they can confirm that the liquids are different (boiling point, viscosity, density, etc.).	240
Solid Characteristics	Students can describe characteristics of solids that can be used to identify solids that are different or the same (appearance, texture, color, etc). Students can recall prior knowledge about how they can confirm that the liquids are different (density, size, melting point, etc.).	245

The following observations are typical from the day 2 activities. Day 2 begins with the students completing their assigned data collection. As has been observed in the school during other activities, for some students the concepts of radius, diameter, area and volume are unclear to them. These students can define the equation for volume of a cylinder given to them, but they have a difficult time explaining the concept and relationship it embodies. Students are very familiar with volume and area of rectangles and cubes, but circles and cylinders are not less familiar. This was observed more in the science classes because the math classroom had posters lining the walls explaining what radius, diameter, circumference, area, and volume. A general weakness of students at the school is their graphing abilities. Students understand how to plot points, create a line graph or a bar graph but have difficulty assigning appropriate number scales to the axis. However, since their numbers were values they had generated personally, the task of labeling axis appeared less difficult to them. During the second day students were able to quickly spot when there had been an error in one of the calculation steps leading to a reported value. Students were very supportive and frequently double-checked values for their classmates. The classes were very quick to be able to describe the observed similarities and differences between the various liquids and solids.

Some specific observations of student learning from Day 2 include the following:

- Students were able to successfully calculate volumes of cylinders given the appropriate equation
- Students were able to describe past knowledge of density and use this information to confirm their volume measurements
- Students were able to properly display their test data graphically
- Students could ask and describe which information would be useful when making wise engineering design choices the next day

Day 3. Engineering Design

During the last day of the lesson, students are provided a list of materials and asked to design a custom surface that can hold the maximum number of drops of liquid. As part of their design considerations, they must record the cost of their design. The class is given property information for each of the liquids and materials they have available. Students are asked to minimize cost and weight in their design. Groups, once again, report their results on the board. A final discussion of their observations culminates the three-day lesson.

The students are asked to first outline their design before going back to collect the required materials. This allows each group to critically consider how they will approach the design objectives before diving into the materials. Once they have described their design they then need to follow the test procedures used in day 1. The final aspect of their design is to determine the weight and cost of their design and report the final results on the board.

By the end of day 3, the following learning should be achieved:

(a) Communication – students are able to describe their design solution in such a way that it can be duplicated.

(b) Critical Thinking – students are able to demonstrate logical reasoning skills as they develop their own design solution to meet each of the design requirements.

Table 3: Day 3 Learning Outcomes

Learning Outcome	Evidence Sought	# Students Successful
Communication	Students are able to describe their design solution and explain why they made the decisions they made. Students can communicate to peers their design and results.	118
Critical Thinking	Students demonstrate logical reasoning skills as they develop their design. Students can explain how their design meets the design requirements.	101

Conclusions

Data was collected in the form of worksheets the students completed throughout the three day lesson. Their worksheets were assessed to demonstrate successful learning outcomes for each day. In addition, students were given a reflection survey three weeks after they participated in the lesson. The survey was used to help instructors assess which concepts were retained by the students. It was also a way to obtain direct feedback from the students' on what they enjoyed, learned, and would change in the lesson.

Overall, 94% of students were successful during the first day at being able to pose a hypothesis, follow procedures, and collect and record data. About 75% were further successful at understanding and making conclusions based on observed behaviors observed from the first and second day. Then finally 40% students demonstrated understanding of the higher level outcomes on the third day. The general trend in successful learning outcome completion during the lesson was expected. The learning outcomes transitioned towards more critical thinking skills after each successive day, therefore it was expected that the majority of the students would be successful during the first day. It was the hope that the nature of the lesson would enable a greater percentage of success as the lesson developed towards higher thinking outcomes and while a decrease was seen in the results the students were able to feel successful with a complex lesson. One aspect that may improve the numbers would be the available class time to complete the activity; many students may have been able to complete all three activities if they had been able to have more time.

While developing and implementing this activity a lot was revealed about how to make math, science, technology, and engineering exciting to high school students. This lesson required that a very complicated engineering research topic be made accessible to high school students. The biggest lesson learned was how critical it was to understand the students' prior knowledge. Across the two years and fifteen implementations of this lesson there were observable differences among the students' familiarity with following procedures, recognizing appropriate dimensions, and general topics of area, volume, and density. One way to ensure that all students have an equal opportunity to successfully enter the lesson is to provide the class with an overview of topics including radius, diameter, area, and volume. This overview can be done any time before the start of the lesson.

The lesson implementation was most successful and students exhibited an increased occurrence of staying on task, when they were given the opportunity to share their findings with peers. Students were seen assisting peers in verifying the results being recorded on the board. The classes seemed to operate under the mentality that they were working towards a common goal; for the success of the individual there needed to be success for the entire group. Therefore, it was important to publicly recognize this quality in the students and allow those types of sharing opportunities throughout the lesson.

It was observed that in some classes the students were naturally excited to experiment with the materials on the third day. However, others did not find the structure rigid enough, and complained when it was time for them to create and test their own design solution. After the first years' implementation students suggested that the design portion of the activity to be made into a competition with a prize for the designs. This idea was implemented during the second year to mixed student reviews. Some classes were very motivated by the idea that they could compete against their peers while other classes became less motivated by the idea of the competition. The less motivated groups tended to be the classes composed of younger students. This would be a critical aspect to understand better in the classes to ensure that there was full participation in the design activity.

Recommendations and Extensions

In each class the author distributed an activity reflection after the final day of the lesson. The goal of the questioner was discover:

- What students' attitudes regarding the activity. Did they like or dislike the lesson or parts of the lesson.
- What students would suggest for improving the activity. If they didn't like it, then what would they do differently for next year. If they liked it, what specifically did they like.
- What students learned or what surprised them during the lesson.

The two years and five implementations of the Penny Surface Properties lesson in a rural agriculturally-oriented community led to several recommendations for future use of this activity. Some resulted from student feedback questionnaires, others from instructor and graduate assistant ideas.

1. Expand testing to allow variations in penny sizes and shapes. This could reinforce concepts of area and volume for different geometric shapes.
2. Conduct property measurements for liquids prior to the Penny Surface Properties experiment. This can be done easily in any science classroom and would benefit students in that they could have a better understanding of the liquids they are testing.
3. Allow students to design an additional exercise to explore additional questions of interest to them. Then discuss the value and benefits of this recommendation.