A Novel, Hands-On Approach to Teaching Heat Transfer

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ABSTRACT

The topic of heat transfer is traditionally taught as an upper level, lecture-style course to mechanical engineering students. Such courses do not provide students with ways to see and feel the important heat transfer concepts at hand. As a way to overcome this, novel, hands-on workshops have been designed and implemented into a heat transfer class taught to junior level mechanical engineering students. Two types of experimental workshops were created and used in two different years of a section of a heat transfer class. In the first year, twelve workshops were designed which included live demos so that the students could see and feel different modes of heat transfer while taking data and seeing real-time plots of temperature and heat flux in different experiments. The workshop introduced each topic the students would be learning in the lecture and was performed the week before the actual lecture on the topic. Each workshop included easily available materials, thermocouples, heat flux sensors, and data acquisition instruments for the students to use. The workshops also served replacements for what would be the third lecture of the week. Results from a concept inventory test given at the end of the first year showed a significant difference on certain question between an experimental group of students who had the workshops and a control group who took the traditional class lecture. However, there were still concepts and topics that the experimental group did not show improvement. They also showed a lack of improvement in their problem solving skills for quiz and test problems.

For the second year of the experiment, the workshops were restructured quite a bit. The original 12 workshop format was cut down to only six in order to focus on the ones the students seemed to have benefitted from the most. The workshops were also changed into a video-enhanced format where the students would watch a video of the experiment being done while also having the materials in front of them to place their hands on themselves. The students could therefore see and feel what was physically happening and still perform the experiment while watching real-time, pre-recorded plots of heat flux and temperature without worrying about making sure their setup was right and acquiring good results. The new video-enhanced workshops also included control volume and resistance diagrams for each experiment in order to help the students relate the workshops and concepts back to problems on their quizzes and tests. Results from these workshops seemed to show some statistical significance between the experimental and control groups on concept questions given on quizzes throughout the semester, but there was no difference on any questions from the ten concept questions given on the final exam. However, surveys taken by the students indicate that they believed the workshops did help them to understand the concepts in a real-world sense and that they helped them understand the class material better overall.

Aside from the results of the workshops on the students learning, this study concludes with an analysis of important heat transfer concepts and how to test them. There is much debate about the underlying concepts in the topic of heat transfer and a thorough analysis on what specific concepts are important for students to know must be addressed. Many heat transfer concept questions on current concept inventories have more to do with thermodynamics and the mixing of the two topics is itself a misconception.

DEDICATION

To my sister, Sister Chiara Cirenza, and all of the Dominican Sisters of St. Cecilia for their endless prayers, and to my parents and brother for their unwavering support.

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ATTRIBUTION

Several colleagues aided in the writing and research behind one of my chapters presented as part of this thesis. A brief description of their contributions is included here.

Chapter 2: Hands-On Workshops to Assist in Students' Conceptual Understanding of Heat Transfer.

Thomas E. Diller, Ph.D., is currently a mechanical engineering professor at Virginia Tech specializing in heat transfer. Dr. Diller served as co-author on this paper and assisted in the creation, design, and structure of the workshops. He also assisted in creating a list of important concepts and concept questions to ask the students.

Christopher B. Williams, Ph.D., is currently a mechanical engineering professor at Virginia Tech specializing in additive manufacturing. Dr. Williams also served as co-author on this paper and assisted in creating surveys to qualitatively evaluate the students. He also assisted in the creation of the workshops, especially the challenge-based worksheet portions.

Rande J. Cherry, M.S., is currently a graduate research assistant in the heat transfer measurements lab at Virginia Tech. Mr. Cherry also assisted in the design and creation of the workshops and getting the workshops set up for the students every week for the first semester. He also assisted with guiding the students through the workshops and grading them.

Karthik Balasubramanian, M.S., is currently a graduate research assistant in the heat transfer measurements lab at Virginia Tech. Mr. Balasubramanian assisted in setting up and guiding the students through the workshops in the second semester. He also assisted in the grading of the workshops and data collecting.

Tim J. O'Brien, M.S., is currently a graduate research assistant and Ph.D. student at Virginia Tech. Mr. O'Brien assisted in setting up and guiding the students through the workshops in the second semester. He also assisted in the grading of the workshops.

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Chapter 1: Introduction and Thesis Organization

1.1 Introduction

The subject of heat transfer is a crucial part of the undergraduate mechanical engineering curriculum because its countless applications can be seen in all types of different industries. Anywhere where a temperature difference is taking place, a transfer of heat must also be occurring. In such a fast-paced, growing, industrial world, the control and monitoring of heat transfer plays an important role in making more energy-efficient products and processes because heat itself is a flow of energy. For this reason, a solid and fundamental understanding of heat transfer is key for anyone wishing to work in the mechanical engineering side of industry.

1.2 Organization

This thesis is organized into a single manuscript. The manuscript corresponds to the second chapter of this thesis. References for each can be found at the end of each chapter. Figures are embedded into the text to allow for ease of reading. Supplementary material can be found in the Appendices.

The second chapter of this thesis focuses on a two year study in which hands-on workshops were implemented into two semesters of a junior level heat transfer class at Virginia Tech. The first semester involved workshops in which students collected heat flux and temperature data themselves for different experiments whereas the second semester utilized videos that the students could follow along with but still feel and use the lab materials.

Chapter 2: Hands-On Workshops to Assist in Students' Conceptual Understanding of Heat Transfer

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2.1 Abstract

A two-year study was conducted to engage undergraduate mechanical engineering students to approach heat transfer education in an active, hands-on manner and excite them to pursue research and graduate studies in the field. Physical workshops were designed and implemented into a junior level heat transfer class, allowing students to feel and observe heat transfer using heat flux and temperature sensors that provided real-time data. These instruments, coupled with open-ended, challenge-based pedagogy, provided opportunities for students to explore important heat transfer concepts, such as the differences between heat and temperature. The conceptual knowledge of the students was assessed through concept-specific questions. These results were compared to those of a control group who took the traditional lecture without the workshops. The results yielded significantly higher scores for the experimental group in the first year but not as much of a difference in the second year, which used video-enhanced workshops in place of the purely hands-on workshops. In addition to concept questions, surveys taken by the students reveal that the students much preferred the workshops over not having them and believed the workshops strongly enhanced their learning by giving them a real, hands-on feel. Future work entails (i) identifying the most important heat transfer concepts for students to grasp in order to understand the fundamentals of the discipline, (ii) investigating additional ways to enhance students' conceptual knowledge, (iii) improving their problem solving skills, and (iv) manufacturing low-cost sensors to make them easily accessible to any student taking a heat transfer course.

2.2 Introduction

Heat transfer is part of the core of all Mechanical Engineering curricula, and its concepts can be found throughout science curricula. The concepts of heat and work were developed many years ago to explain and solve real physical problems such as the temperature increase experienced in gun boring and how to use steam to pump water from the coal mines in England. Its relevance continues today as the world learns to power society with the least impact on the environment. Whenever energy production or use is discussed, heat transfer processes are integral to the efficiency of the systems.

Given the importance of heat transfer, it is most troubling that recent research shows that students have a limited understanding of heat transfer principles even after the completion of one or more heat transfer courses [1]. Specifically, students have shown (i) a significant lack of conceptual understanding of heat transfer principles, (ii) an inability to transfer knowledge to subsequent courses and out-of-context problems, and (iii) an insufficient transformation from novice to "competent practitioner."

Heat transfer is traditionally taught using a deductive instructional style. Deductive instruction is characterized by an instructor presenting and defining a general concept, providing examples that demonstrate the idea, giving students practice in solving similar problems, and finally, testing their ability to do the same tasks on exams. This "skill-and-drill" approach allows students to approach learning passively, and does not challenge them to modify their prior understanding. Little attention is paid to the physical world phenomena that the concepts explain or what types of practical problems that they can be used to solve [2]. This mode of instruction is especially limiting when teaching abstract concepts, such as those encountered in a heat transfer course. In addition, heat cannot be seen or even directly experienced. The human body has very

well developed sensors for temperature, but not for heat transfer. For example, humans' temperature sensors can cause confusion as to why a metal object feels colder at room temperature than a wood object at the same temperature, or why one is burned by a pie pan taken from the oven, but unaffected by a piece of aluminum foil at the same temperature. Traditional lecture style courses are limited in how well they can convey certain difficult concepts. While they stress important ideas such as setting up control volumes and energy balances, they do not do a good job helping students distinguish between the three modes of heat transfer in real world problems (conduction, convection, and radiation), nor can they offer physical representations of problems to allow students to feel heat transfer taking place in different situations. This results in a lack of understanding of the underlying concepts of heat transfer, which is vital to build a foundation from which to advance one's understanding.

Although other engineering and science curricula can make similar claims, these problems are usually overcome by introducing measurement sensors and instruments to easily quantify and demonstrate the associated phenomena. For example, in electrical engineering, most everyone is introduced to voltmeters and ammeters early in life. However, there is usually no analog in the context of heat transfer; while everyone knows about temperature sensors of some type, students have rarely seen a direct measurement of heat transfer, even though these sensors have been available commercially for fifty years. This is similar to explaining the concepts of electrical current without ever seeing a measurement with an ammeter. Consequently, the concept of heat transfer remains abstract and difficult to understand because it can't be visualized and isn't normally measured.

Heat transfer laboratory courses have been developed to provide opportunities for students to make connections between the theory of their lecture-based course and the practical

world. However, these lab courses are taught in a deductive manner: students follow "cookbook" structured experiments where the outcome is already known [3]. Thus the lab is more focused on students' ability to follow instructions to achieve a desired outcome rather than being challenged to explore the connection between theory and practice. The deductive structure of existing laboratories does not provide the freedom for students to challenge and modify their existing knowledge framework. Moreover, the existing labs for heat transfer use only temperature measurements for thermal phenomena. There are no known undergraduate labs which use actual measurements of heat transfer or heat flux. This is rather amazing given that heat transfer is the subject of the course.

Despite completing several courses in thermal and transport sciences, a significant number of students have misconceptions about simple heat transfer processes [4, 5, 6]. Through the development of the "Thermal and Transport Concept Inventory" (TTCI) test [7], it has been observed that students possessed "robust misconceptions" about the differences between

- heat, energy and temperature,
- rate and amount of transfer (e.g., heat transfer, momentum transfer, mass transfer),
- steady-state and equilibrium processes [8].

In their experiments with Chemical Engineering senior students, it was found that one-third to one-half of the students had misconceptions about these concepts as recorded by the TTCI [9]. However, the above three concepts are specific to heat transfer students in chemical engineering and include ideas from thermodynamics as well. Since heat transfer is taught differently to mechanical engineering students, a new list of six concepts specific to mechanical engineering students in heat transfer is proposed. This list is shown below in Table 1.

Table 1: Important heat transfer concepts for mechanical engineering students

Concept Number	Concept
1	Heat transfer is inversely proportional to thermal resistance
2	Heat transfer requires a temperature difference (source and sink)
3	Temperature change requires an energy transfer
4	Energy balance must be satisfied (parallel and series pathways)
5	Fluid flow carries thermal energy while it transfers by conduction
6	Radiation is purely a surface phenomenon with no medium required

The current work reports on the results of research to integrate Challenge-Based Workshops (CBW) into existing heat transfer courses. This provides hands-on activities with real-world challenges to help the students relate heat transfer to their conceptual framework. The effects on both student misconceptions and retention of basic concepts are evaluated.

2.3 Workshop Background and Rationale

Although the problem of student misconceptions has been clearly identified, an accepted pedagogical method to address these learning deficiencies has not yet been demonstrated. As a step toward addressing this gap, the authors propose an approach to heat transfer education that is centered around hands-on, challenge-based workshops (CBW) that promote discovery and conceptual connections to observed and measured physical phenomena.

Inductive pedagogies such as CBW are centered in student engagement. A survey of neurological and psychological research found strong support for these approaches, specifically showing that (i) students understood information better when they were forced to link it to their existing cognitive structures, (ii) students were more motivated to learn when they could see the potential for impact, (iii) there was a greater chance of knowledge transfer, and (iv) students' problem-solving skills were improved [10]. Conversely, the deductive learning mode does not reflect what we know about how people learn – following the constructivist learning theory, it is known that students form knowledge representations of new information by building on their

previous knowledge and experiences [11]. If the new information has few connections to what they already know, learning will not occur nor will students be motivated to learn [12]. Thus, effective instruction must provide experiences in which students actively construct knowledge by adjusting, rejecting, or modifying their prior beliefs and understanding based on their experiences [2]. Deductive instruction does not facilitate this mode of learning; its "skill-and-drill" approach allows students to approach learning passively, and does not challenge them to modify their prior understanding.

The authors' CBW approach is grounded in an existing pedagogy that blends inductive and deductive processes: Challenge-Based Instruction (CBI). CBI begins first with an inquiry or challenge (i.e., a question to be answered or a hypothesis to be tested). Following the principles of the Legacy Cycle of instruction, the students are then (i) asked to formulate their initial thoughts, (ii) receive expert perspectives, (iii) research and revise their solution to the challenge, and finally, (iv) present a final conclusion via presentation, report, or examination [13]. This cycle presents a blended inductive and deductive mode to instruction: the need for learning is motivated by an authentic problem; the challenge causes the students to continuously iterate their conceptual understanding of the domain by consulting the expert (through small lectures), and discussions with their teammates. CBI modules [14] were created [15] with support from NSF for a variety of topics in Bioengineering [16]. The method was shown to improve students' performance with open-ended problems [17, 18, 19]. Inquiry-based learning approaches, such as CBI, have been found to be "more effective than traditional science instruction at improving academic achievement, and the development of thinking, problem-solving and laboratory skills" [2], and to enhance understanding of critical engineering concepts [20, 21].

A key facet of the CBW approach in heat transfer instruction is the integration of hands-on workshops into the existing course. The integration of hands-on activities into courses has shown significant learning gains for students across several domains. Faculty have used interactive learning in small groups with hands-on demonstrations to enhance fluids and heat transfer learning in the Chemical Engineering curriculum [22, 23, 24, 25]. RPI has instituted mobile studios, consisting of a suite of instruments that are connected to PC's via USB for observing and testing electrical theories [26]. A similar approach (TEAL) has been instituted at MIT for freshmen physics classes with positive results [27]. Virginia Tech has created a "lab-in-a-box", which is an inexpensive set of instruments and a bread-board to allow students to perform electronic experiments themselves [28].

The heat transfer workshops in the current study are modeled after the Challenge-Based Instruction (CBI) pedagogy and are designed specifically to target students' common heat transfer misconceptions. The workshops are heavily focused in providing hands-on experiences and allowing students to explore connections between theory and the physical world. As such, the workshops feature state-of-the-art sensors that measure both temperature and heat flux (heat transfer per area).

This paper consists of a two-year study on the use of two different types of hands-on, heat transfer workshops.

(1) The first year consisted of having the students use heat flux and temperature sensors to take data for different situations and scenarios that related to topics from the lectures. By using these sensors, students were able to physically explore abstract concepts such as thermal energy and heat transfer and thus facilitate learning through the active reconfiguration of their cognitive structure. There were twelve workshops given

throughout the semester covering each topic introduced in the lectures. The workshops were given the week before the lecture covering the topic, thus the students had no prior knowledge of the material going into each workshop.

(2) The workshops were then restructured for the second year of the study. It was observed that students spent too much time on the experimental aspect and worrying about acquiring good data. In order to overcome this and help them focus more on the concepts at hand, the workshops in the second year consisted of videos of the experiment with real-time data and plots. The physical setup, however, was still given to the students so that they could perform the experiment while simultaneously watching the videos without worrying about acquiring good data. The workshops were consolidated down to only six to focus on the important concepts and topics and they were given a few days after the topics they covered were introduced in lecture.

In this paper, the authors present the CBW concept, describe its implementation, and report on the results of the assessment of the CBW on student learning. It was hypothesized that performing simultaneous temperature and heat flux measurements in the context of carefully designed challenge-based learning experiences would (i) improve students' conceptual understanding, (ii) improve their problem-solving abilities, and (iii) improve their ability to transfer knowledge to other courses and contexts.

2.4 First Semester Experimental Approach and Results

The following discusses the first semester implementing the experimental workshops. These workshops were offered in place of the third lecture of a section of a 3-lecture-a-week junior level heat transfer class. The experimental workshop section consisted of 68 students. A group consisting of 58 students taking the traditional lecture class without the workshops was

used as a control group. Aside from the workshops in the experimental section, all other aspects of the two classes were the same, including instructor, tests, weekly quizzes and homework.

2.4.1 Challenge-Based Workshops Description

The authors implemented CBW in a junior-level heat transfer class at a large land-grant university. Unlike traditional lab classes, CBWs are given to the students in a structured format that includes a challenge question and five step approach to guide the students in the direction of both solving the challenge question and understanding the underlying concepts. The challenge every week consisted of a hypothetical scenario intended to make the students imagine they were engineers working in industry trying to solve a problem for their employer.

Following the CBI technique, students work to solve the challenge question via research and experimentation through a five step process inspired by previous CBI pedagogy:

[1] The first step was to generate ideas about the problem. The students were to establish an experimental plan to answer the challenge question. This step always included questions intended to point the students in the right direction and a hypothesis for them to predict what was going to happen.

[2] Step two provided some background information to the students which related to the challenge question they were attempting to solve. Pertinent equations were provided as well as some description of how they were to be used.

[3] In Step three, the students were asked to show which equations they were going to actually use and how they were going to perform their experiment. This usually involved questions relating to how they were going to use their heat flux sensors and thermocouples.

[4] Step four involved the crux of the experiment. Some instructions for how they were to use the data acquisition software were provided along with instructions for how to run the

experiment. The students were then asked to evaluate the results of their experiment by solving for certain variables using the data they collected and then answering the challenge question posed to them at the start. Many of their results included graphs that they could both see in real time and examine after the data was taken to assist them in understanding what was physically happening.

[5] Step five was a reflection step which included questions asking about the concepts that were stressed during the workshop and was intended to gauge what the students learned throughout the process.

For the particular purpose of using this CBW approach for heat transfer, every workshop consisted of a physical setup using thermocouples and heat flux sensors. While many students with no background in the subject matter have a basic understanding of temperature, it is hard for them to distinguish between temperature and heat flux and understand how the two relate. Therefore, it was necessary to utilize both types of sensors in the workshops so that the students could physically touch and better understand how they worked.

The sensors were connected to a data acquisition instrument (DAQ) provided by National Instruments and the software: LabVIEW, also by National Instruments, was used to collect the heat flux and temperature measurements from the sensors in real time. Most workshops used the LabVIEW software so that the students could see plots of the measurements in real time. The students then would run a pre-written MATLAB program which would take the data and output any relevant plots and values the students would use for their particular experiment. An introduction to the sensors was given in the first workshop. The students were provided with a metal and plastic plate, a heater, and surface thermocouples and heat flux sensors. They were first allowed to run the LabVIEW software and investigate with the sensors to see how heat flux

and temperature are measured differently. They then used a heater to heat the plastic and metal plates with the sensors attached and got to see how the surface temperature and heat flux measurements differed for the two materials in real time. Every workshop following the first continued to use both types of sensors in different experiments.

The 65 student experimental section was split into three groups of equal size (about 21 students per group) so they could have more individualized attention during the workshops. Within those groups, students were split into teams of two or three to perform the workshops so that each student could touch the materials and feel the heat transfer processes first hand.

Each workshop was intended to address any misconceptions associated with the specific topic at hand. The workshop topics were chosen to be those presented in the lectures the following week. This approach provided students the opportunity to gain physical experiences with heat transfer phenomena first as a means for motivating their learning of the theoretical principles and relationships. A list of the workshop topics in order of the weeks they were given is presented in Table 2 along with the specific concepts stressed. The workshop topics followed those covered in lectures and the workshops themselves were intended to focus on the proposed concepts from Table 1 in Section 2.2.

Table 2: Summary of Workshops for Each Week

Week	Topic Covered in Workshop	Concept(s) Stressed
1	Introduction to software, thermocouples, and heat flux sensors. Conduction heat transfer for materials of different thermal properties.	1, 2, 3
2	How fins affect convective heat transfer, convective coefficient.	2, 3
3	Understand transient heat transfer- how heat flux and temperature change with time.	2, 3
4	Work more with transient heat transfer and understand thermal resistance and link it to conduction. Semi-infinite materials.	1, 4
5	Boundary layers and how they affect convective heat transfer.	2
6	Apply ideas of convective heat transfer to internal flow.	2, 3, 5
7	Internal flow part 2: overall heat transfer coefficient.	2, 3, 5
8	Mass transfer process and relationship of heat and mass transfer.	

9	Computer simulation of a heat exchanger.	2, 3, 5
10	Radiant heat transfer, view factors, emissivity and absorptivity.	3, 6
11	Radiation part 2: gray bodies and radiosity.	3, 6
12	Use thermal camera to look at experiments from previous workshops.	3, 6

Workshop 2 is presented in detail here to provide an example of CBW. The objective of this workshop was for the students to learn what a fin is and how it affects heat transfer. In this workshop, the students were introduced to the idea of heat transfer coefficients. The challenge presented was to determine the convective coefficient, overall heat transfer, and efficiency of the given fin. Provided for the students was a piece of metal heated at the base to act as a fin, a fan with low and high settings to provide different heat transfer coefficients, thermocouples and a heat flux sensor attached to the fin, and data software and instructions on how to run the experiment.

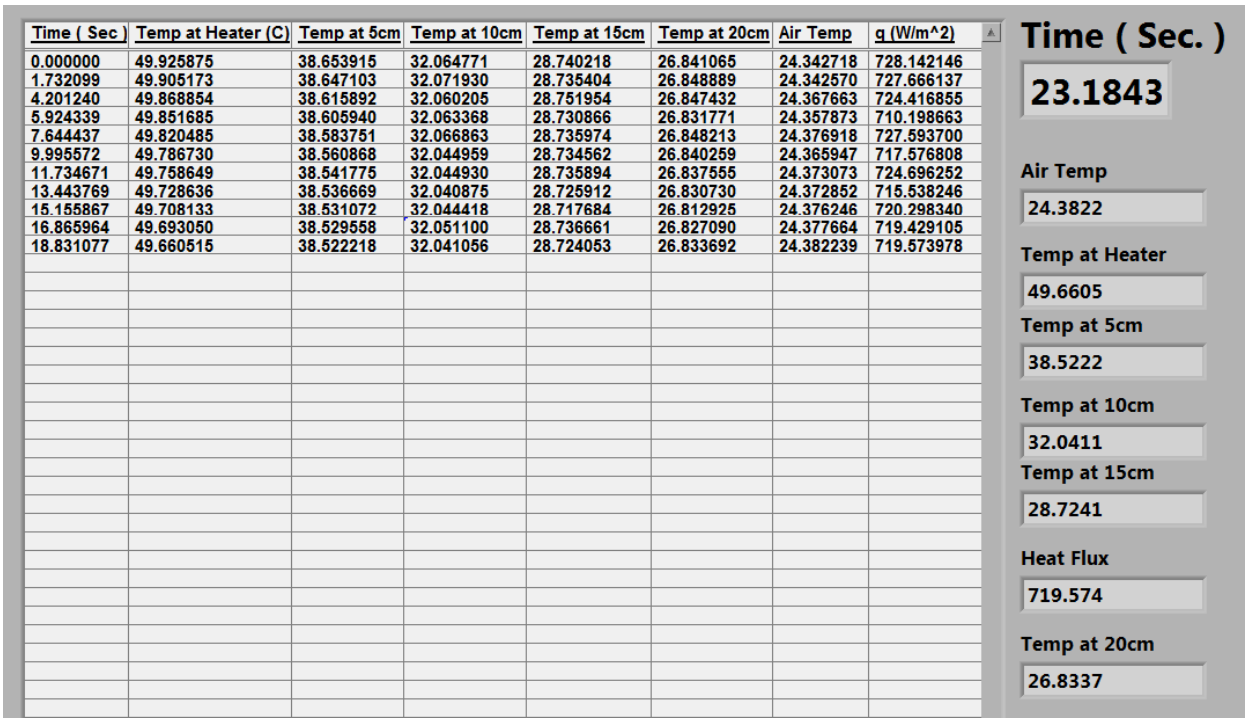
Step 1: The students were asked to generate ideas about what a fin is, how it works, and what purpose it provides. They were asked questions to help lead them in the right direction.

Step 2: The students were provided information about fins and the relevant equations associated with them. All of the terms in the equation were provided.

Step 3: The students then revised their earlier ideas about fins with the new information.

Step 4: The experiment was conducted by the students. In this particular workshop, they created low and high fan air speeds on the fin and watched real time data of temperature across it using the LabVIEW software. A screenshot of the LabVIEW program is shown in Figure 1a. They then ran a MATLAB code which outputted plots and the heat flux values to assist them in calculating convective coefficients, total heat transfer, and efficiencies. Examples of the output data from the MATLAB program are shown in Figures 1b and 1c.

Step 5: For the final step, the students answered reflective questions related to what they learned. They were asked general questions about fins and how their performance changes based on convective coefficients.



Time (Sec)	Temp at Heater (C)	Temp at 5cm	Temp at 10cm	Temp at 15cm	Temp at 20cm	Air Temp	q (W/m^2)
0.000000	49.925875	38.653915	32.064771	28.740218	26.841065	24.342718	728.142146
1.732099	49.905173	38.647103	32.071930	28.735404	26.848889	24.342570	727.666137
4.201240	49.868854	38.615892	32.060205	28.751954	26.847432	24.367663	724.416855
5.924339	49.851685	38.605940	32.063368	28.730866	26.831771	24.357873	710.198663
7.644437	49.820485	38.583751	32.066863	28.735974	26.848213	24.376918	727.593700
9.995572	49.786730	38.560868	32.044959	28.734562	26.840259	24.365947	717.576808
11.734671	49.758649	38.541775	32.044930	28.735894	26.837555	24.373073	724.696252
13.443769	49.728636	38.536669	32.040875	28.725912	26.830730	24.372852	715.538246
15.155867	49.708133	38.531072	32.044418	28.717684	26.812925	24.376246	720.298340
16.865964	49.693050	38.529558	32.051100	28.736661	26.827090	24.377664	719.429105
18.831077	49.660515	38.522218	32.041056	28.724053	26.833692	24.382239	719.573978

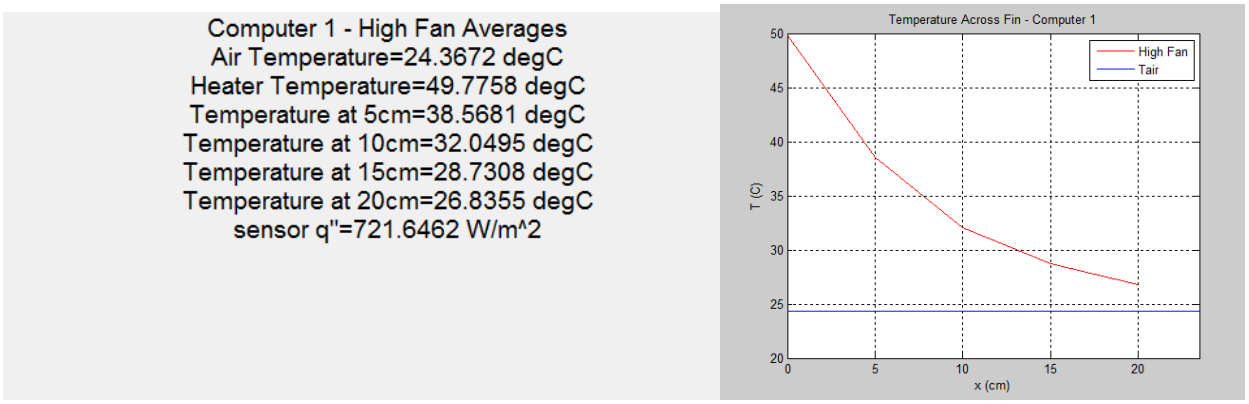


Figure 1 a) (top) Screen shot of the LabVIEW program showing real time temperature measurements from the fin. **b)** (bottom right) Averaged output data from thermocouples and heat flux sensors calculated using MATLAB. **c)** (bottom left) Resultant plots from MATLAB

The goal of this workshop was for the students to learn the basics of convective and conductive heat transfer and how they are related. The unique challenge-based and hands-on

approach is implemented. They entered the workshop with no preconceived notions of convective heat transfer or fins because they had not been taught the material in lecture yet. The main challenge, therefore, was to learn how fins physically work. Using the heat flux sensor combined with thermocouples and doing some calculations gave them physical experience with heat transfer coefficients and the basics of convection. For the specific case in figure 1, using the following equation: $q''=h(T_s-T_\infty)$, the students could calculate the heat transfer coefficient for the high fan speed to be $h=722/(32.0-24.4)=95W/m^2K$ (the heat flux sensor was placed at the 10cm mark on the fin). This direct calculation for h was only possible by performing simultanteous measurements of heat flux and temperature. Most importantly perhaps, this workshop gave them the opportunity to actually put their hands on the fin and feel the change in temperature from the fin's base to its tip. This, combined with real time plots, provided a new and innovative learning experience for fin heat transfer.

2.4.2 Assessment Methodology

In order to evaluate the effect the workshops had on the students, a concept inventory test was given to them at the beginning and end of the semester. The pretest featured five questions from the TTCI and was given not only to compare against a post-test, but to ensure that the control and experimental groups' understanding at the beginning of the study could be considered equivalent. At the end of the semester, the entire 19 question TTCI was given to each section to see if the workshops played a role in helping the students better understand the basic concepts in heat transfer. The questions were taken from the Heat Transfer section of the "Thermal and Transport Concept Inventory" by Ron L. Miller, the "AIChE Concept Warehouse," and the authors. The questions from both the pre and post tests featured a mix of ones specific to the six concepts from Table 1 in Section 2.2 and control questions geared more

toward thermodynamics ideas. The questions are separated into the different concepts in the following section.

JMP 11, a statistical analysis software package, was used to examine statistical differences between the performances of the two groups of students. Statistically significant differences were assumed at a significance level (α) of 0.05.

2.4.3 Assessment Results

Results from the pre-test showed no significant difference between the groups for any of the five questions. As class assignments were made at random, it can be assumed that the two sections started off without any advantages or prior knowledge regarding heat transfer concepts. The scores on the five question pretest for both groups along with the standard errors and p-values is displayed in Table 3. As mentioned, using an alpha value of .05, none of these questions yield any statistically significant difference.

Table 3: Scores on initial concept quiz

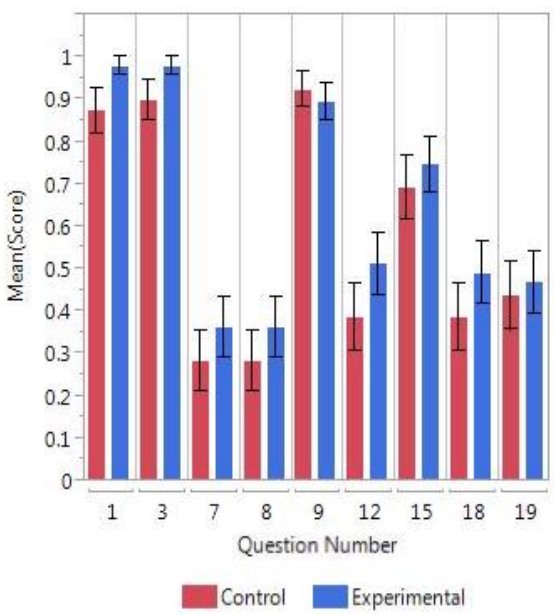
Question Number	Control Score ± SE (%)	Experimental Score ± SE (%)	P-Value
1	71.1±7.46	83.0±5.54	0.1903
2	31.6±7.64	44.7±7.33	0.2159
3	86.8±5.56	95.7±2.98	0.1356
4	50.0±8.22	68.1±6.87	0.0904
5	47.4±8.21	63.8±7.08	0.1277

The results from the 19-question concept inventory given at the end of the semester show a statistically significant difference both in overall scores between the two sections and for certain individual questions. Table 4 shows the results on the test overall as well as the questions showing statistical significance. A Wilcoxon ranked sum test was performed and revealed that the difference in the overall scores was statistically significant. In addition, the experimental group outscored the control group on 17 of the 19 questions with 4 of the questions yielding statistically significant difference. The mean results for each group (experimental and control)

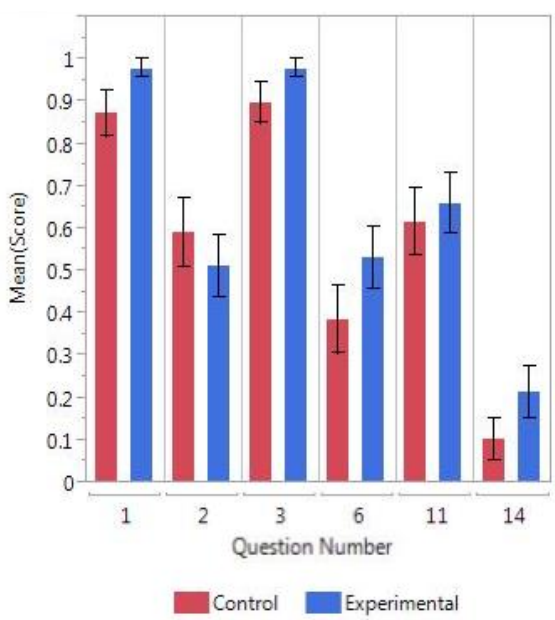
with error bars are shown in Figure 2. The questions have been split into six categories corresponding to the concepts listed in Table 1 in Section 2.2. The questions showing statistically significant differences were 1, 10, 16, and 17. Question 1 is a very general heat and temperature question which falls under concepts 1, 2, and 3 from the list displayed in Table 2. Question 10 has to do with radiation and falls under concept 6. Questions 16 and 17 concern internal flow which link directly to concept 5.

Table 4: Statistically significant results from concept inventory

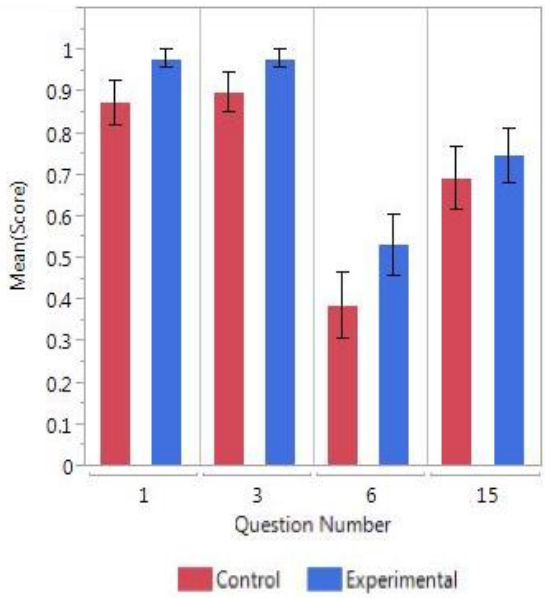
Question Number	Control Score ± SE (%)	Experimental Score ± SE (%)	P-Value
1	87.2±5.42	97.9±2.13	0.0462
10	59.0±7.98	85.1±5.25	0.0061
16	59.0±7.98	80.9±5.80	0.0258
17	48.7±8.11	70.2±6.74	0.0420
Overall Averages:	52.0±2.97	61.8±3.02	0.0289



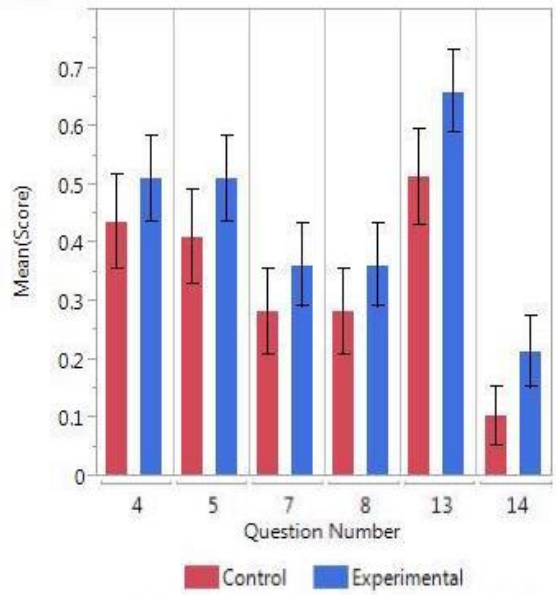
Concept 1: Heat Transfer and Thermal Resistance.



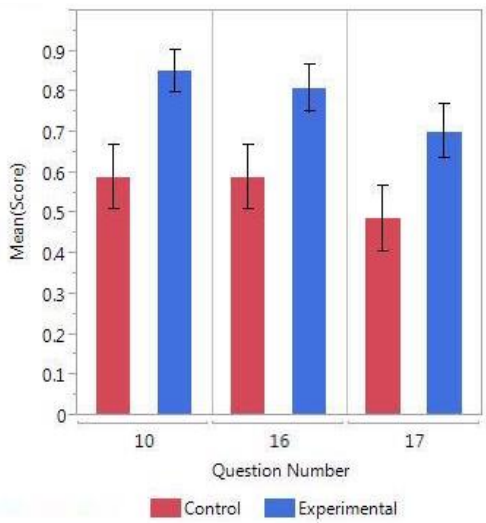
Concept 2: Heat Source and Sink



Concept 3: Temperature Change/ Energy Transfer



Concept 4: Satisfy Energy Balance



Concepts 5 and 6: Fluid Flow and Radiation

Figure 2: Results from final 19-question concept inventory split into the six different concepts they tested.

Question 1 tested the concept of temperature vs heat and energy by asking why a tile floor feels colder than a carpeted floor. The reason for the discrepancy in scores directly links back to the fourth workshop of the semester where the students had to feel the difference between a steel plate and plastic plate and watch how the surface temperature and heat flux

responded over time. This workshop was very similar to the first workshop discussed in section 2.4.1, but the students used their hands to heat the plates instead of a resistance heater and the topic was more focused on thermal resistance. This workshop allowed the students to directly feel and see in real time how heat transfer was occurring in the plates. They got to see the higher heat flux and lower temperature change for the metal because the metal has less thermal resistance than the plastic.

Question 10 tested the concept of radiation: giving emissivity and reflectivity values of two different surfaces at the same temperature and asking which one feels warmer when a person is close to them. This question stresses the difference between temperature and heat flux because while the temperatures for the plates are the same, the heat flux is higher for the black plate. Therefore, a person placing their hands above the plates will feel a difference in heat flux, not temperature. This question links directly to Workshop 10 in which the students got to feel and measure the difference in radiation from heated black and gray plates at the same temperature and see how the heat flux changed on different surfaces right above the plates. While 85 percent of the students in the experimental class answered this correctly, only 59 percent of the control group got it right. Once again, the higher scores from this question can be attributed to the fact that the students were able to directly feel differences in radiation for the different emissivities.

The last questions that showed statistically significant differences were 16 and 17 and had to do with heat transfer in a heated pipe maintained at a constant temperature hotter than the incoming water. The two questions asked what would happen to the average temperature of the water at the exit and overall heat transfer to the water respectively if the mass flow rate was doubled. This question, much like the radiation one, stresses the confusing nature of heat flux and temperature. While the total heat transfer to the water will increase with an increased flow

rate, the outlet temperature will decrease. While fairly basic in nature, the concepts stressed in these questions are important for anyone in the HVAC industry or dealing with internal flow problems. During the semester, there were two back-to-back workshops dealing with internal flow in a pipe. In Workshops 6 and 7, the students directly measured the heat flux and temperature on the inner and outer surfaces of a metal pipe being cooled on the outside by a fan and having hot air flow through it. The fundamental concepts of convective heat transfer in a pipe were covered by feeling the temperature down the length of the pipe (which the experimental section did). Actual measurements of heat flux and temperature provided students with a real physical example of internal flow that could not be achieved in their classroom lecture.

2.4.4 Survey Results

Aside from the concept inventory scores, it is worth looking at how the students performed in the class in general based on their quiz and test scores. Unlike the concept inventory scores, the grades on the quizzes and tests showed no significant difference between the experimental and the control group. Certain test questions were even intended to focus more on the fundamental principles than simply solving problems, but the scores on such questions failed to show any significant difference between the two sections.

A survey was given to the students at the end of the semester to gauge what they thought of the workshops from a qualitative standpoint. Looking at the survey results as a whole, the general consensus was positive. Many students mentioned the benefit of being able to see and feel the modes of heat transfer to apply the concepts they learned in class into physical experiments. Students felt they were able to remember the actual workshops better than the

traditional lectures themselves. They also pointed out the benefit of being guided through the workshops by the TA's and they liked how the workshops involved real-world scenarios.

Looking at what the students disliked about the workshops, the most common responses pointed to the length of the workshops. Almost all of the students mentioned that they felt rushed most of the times to answer all the questions and that the workshops sometimes ran over the allotted time. They also pointed out that some of the number crunching was tedious and excessive when they were required to calculate values based on their measurements. Many students also mentioned how they would sometimes get bad or unreasonable values from their data acquisition. This caused them to try and retake the data or to be confused by what was physically happening.

2.4.5 First Semester Conclusions

Overall the hands-on, challenge-based workshops in the first year did a good job addressing the main misconceptions in heat transfer and helped the students to improve their understanding of the concepts. Looking at the statistically significant results in particular, it is worth noting that the three concept questions showing significant difference relate to the topics that had two workshops made for them as opposed to one. The students had two workshops on conduction and thermal resistance, two on radiation, and two on internal flow. These results stress the importance of not only hands-on, active learning, but also of repetition of a topic to better engrain the concept. The workshops failed, however, in getting the students to apply the concepts to solving problems on their quizzes and tests. While the results on the concept inventory showed a strong statistical difference between the experimental and control groups, neither the quiz grades, test grades, nor final grades showed a significant difference. The

students who took the workshops seemed to be unable to translate the concepts they learned into solving traditionally formulated heat transfer problem sets.

2.5 Retention from First Workshop Semester

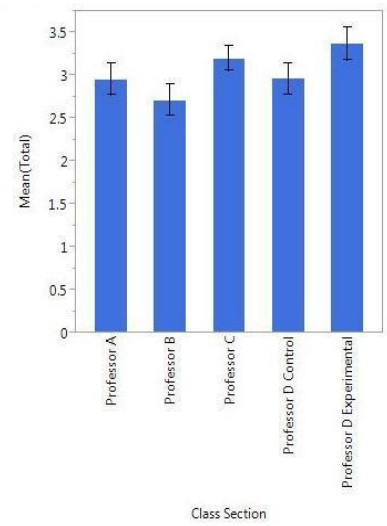


Figure. 3: Total scores on concept retention quiz from all of the previous year's heat transfer class sections.

The retention of the students' conceptual understanding was tested in classes the following semester, after summer break. Seven concept questions were given as a quiz to all of the students who had taken heat transfer the previous year. The quiz was given on their first day of class in the Fall semester of 2014 and they took heat transfer in the spring semester of that same year or earlier. This left a gap of at least three summer months' time since the students had last taken the class. These students came from five different sections of heat transfer taught by four different professors. Two of these classes were taught by the same professor. One was the control group and the other the experimental group who took the class with the workshops.

Results on the quiz showed only a slight difference in the total scores between all the sections with the experimental workshop section attaining the highest score. The bar chart showing the total scores between all of the sections is shown in Figure 3. None of these results, however, yielded any significant difference and not a single section averaged above 3.4 out of 7 on the quiz (48.6%).

The first six questions on the concept retention quiz were multiple choice questions focusing on concepts 1,2,3,4 and 6 from Table 1 in Section 2.2. None of these questions yielded any statistically significant differences comparing the experimental section with the other

sections using an alpha value of 0.05. The seventh question was a simple energy balance problem involving conduction, convection, and radiation with a quantitative answer. As shown in Figure 4, a much higher percentage of students from two of the sections answered this question correctly than the other sections. However, less than one-half of the students retained this fundamental skill over the summer. Most of those who missed this question didn't even attempt to perform an energy balance using a control volume. The two sections that performed the best were the experimental and control groups taught by the professor who gave the workshops. In these classes a strong emphasis was placed on the concept of modeling and using an energy balance. This focus on fundamental concepts (in this case, the concept of using an energy balance) appears to be vital to how well students can retain what they learned.

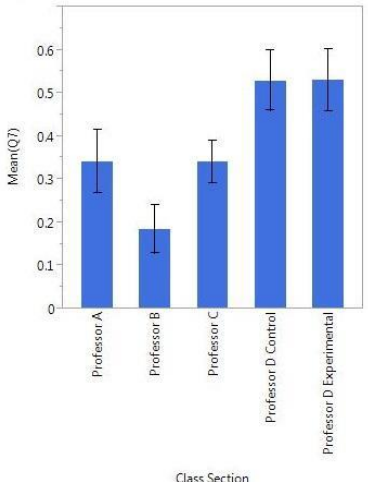


Figure 4: Percentage of students answering the energy balance question correctly for the different sections.

2.6 Second Semester

The second year involved restructuring the workshops to try and get the students to meld conceptual understanding with problem solving skills. The workshops were shortened into hour-long sessions that focused much more on data analysis and less on data acquisition. The number of workshops was reduced from twelve to six and they were included in addition to the three-lecture a week course instead of as a substitute for one of the lectures. The new goal was to help the students focus on the concepts rather than worry about the mechanics of performing the experiments.

2.6.1 Restructured Workshops Format

The data acquisition was all pre-recorded in videos so the students did not have to worry about whether they were using the data acquisition equipment correctly. However, they still performed the experiment as if they were taking the data in order to keep the benefit of feeling the experiment as the plots were being displayed. The workshops ran much smoother because they did not require any real-time measurements. The idea was that the students would have more time to think about the concepts and how they related to the experiment at hand. This format is also easier to transport to other schools since there is no need for expensive sensors and daqs; you only need the physical set ups, which (aside from resistive heaters) can be built from materials found at a home improvement store.

2.6.1.1 Video-Enhanced Learning

One of the goals of the present study was to restructure the workshops in such a way that the students would focus less on acquiring good data from their experiments and more on the concepts at hand. To accomplish this, videos were created to guide the students through the experiment and demonstrate the data acquisition. The students then followed along with the video and performed the same experiment but watched the data being taken on the video itself instead of taking the data themselves. The first two workshops will be described in detail in sections 2.6.1.3 and 2.6.1.4 to serve as examples and better convey how they were structured.

2.6.1.2 General Workshop Structure

The workshops still included the five-step challenge-based instruction method just as in the previous year, but the challenge-based approach was relaxed quite a bit to help the students focus more on what was physically happening rather than making sure they were performing the

experiment correctly. The number of workshops was also cut in half to provide more focus to the important concepts and topics. Six workshops were specifically chosen because they seemed to help the students learn the concepts better than the other workshops both from a quantitative and qualitative standpoint. Table 5 lists a brief summary of all six workshops given to the students throughout the semester. It should be noted that in each workshop, the students were allowed to feel the different heat transfer processes taking place. The concept numbers are included in parenthesis and match up with those of the previous semester's workshops.

Table 5: Summary of six video-enhanced workshops

WS #	Topic / Concept #	Summary
1	Conduction and Thermal Conductivity (1, 2, 3)	• Students are provided with plastic and metal plates • Challenge: Determine which plate is more thermally conductive • Experiment: Place hands on plates to ***feel*** the difference and watch plots of surface temperature and heat flux over time. Relate plots to how the materials feel to determine which is more conductive.
2	Fins (2,3)	• Students are provided with a fin heated at the base and exposed to external convection across the outside • Challenge: Determine how different air speeds blowing across the fin affect its efficiency and total heat transfer. • Experiment: ***Feel*** the temperature gradient across the fin and analyze data of heat flux and temperature across it.
3	External Flow and Boundary Layers (2)	• Students are provided with heated metal plates: one is thick with a constant surface temperature and the other thin with a constant heat flux. • Challenge: Determine which plate should be used to better cool a bed of resistors. • Experiment: Blow air across the plates and analyze the differences in surface temperature and heat flux at the front and back of the plates. ***Feel*** the difference in temperature across the two plates.
4	Internal Flow (2, 3, 5)	• Students are provided with a tube exposed to external convection and a heat gun to blow hot air through the inside • Challenge: Which mass flow rate should be used so that the air blowing through the inside is cooled to 40°C at the exit. • Experiment: Blow hot air down the inside of the tube and look at the resulting flow temperature, wall temperature, and wall heat flux values all the way down its length. ***Feel*** the temperature across the length of the tube.
5	Parallel and Series Thermal Resistance (1, 4)	• Students are provided with heated metal and rubber plates in parallel and series configurations and a cloth to place on top of them. • Challenge: What difference does the cloth make on the total thermal resistance for the heated metal and rubber plates? • Experiment: ***Feel*** the difference in the two heated plates both in parallel and series. Place a cloth over the two in series and feel which one it affects

		more.
6	Radiant Heat Transfer (3, 6)	• Students are provided with thin black and gray sheets heated by black and gray heaters at the same temperature. • Challenge: Determine which configuration of sheets and heaters yields the highest heat transfer to a given sheet. • Experiment: Use data of heat flux and temperature into the metal sheets to determine the emissivities and radiosities of the heaters and sheets. Place hands over the heated plates to ***feel*** the difference in radiation between gray and black surfaces.

2.6.1.3 Workshop 1 in Detail

Just as in the previous semester, the first workshop focused on the basic ideas and concepts of conduction through different materials. The goal was for the students to determine whether a plastic or metal was more thermally conductive. The students were first presented with an imaginary real-world scenario that they were working for an engineering firm and their boss gave them material samples to determine which one was more thermally conductive.

The first three steps were almost identical to those in the previous year. First the students generate ideas and form a hypothesis to answer the challenge question. For this first workshop, a video was provided prior to the workshop which introduced the students to heat flux sensors and thermocouples and using them to take data. Screen shots from this introductory video are provided in Figure 5.

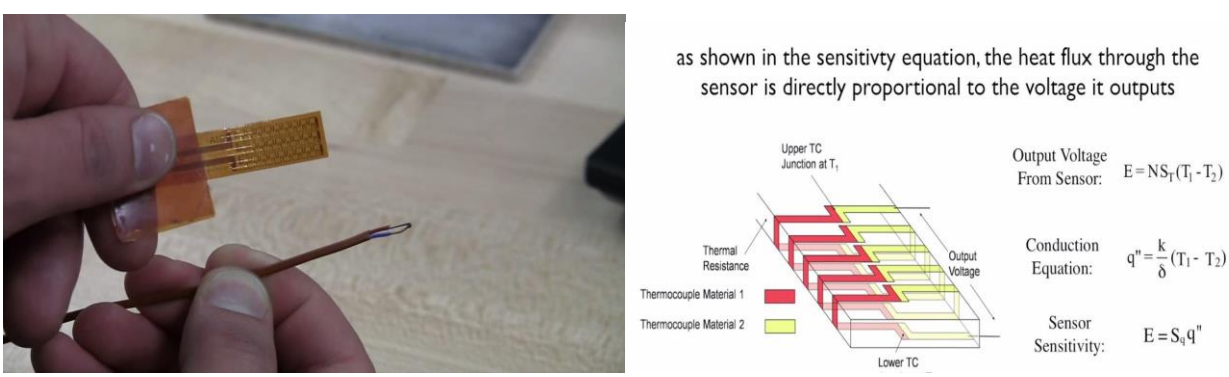


Figure 5: Sensor introductory video screen shots showing (left): An actual heat flux sensor and thermocouple and (right):a heat flux sensor diagram.

While the students were provided with sensors at their station, the actual data from the experiment was recorded in the video and they did not need to acquire it themselves. Unlike in the previous year's workshops, this step also included control volume and thermal resistance diagrams of the physical setup. These were provided to help the students relate their experiment with the problem solving process and the very important concept of using a control volume and energy balance. The control volume and thermal resistance diagrams are displayed in Figure 6.

The next step was to perform the actual experiment. Unlike the previous year when the students had to put the sensors on the materials and acquire the data themselves, videos were provided in this step for the students to watch and follow along with the materials provided. The videos showed someone placing their hands on the pieces of metal and plastic split screened with real time plots of the temperature and heat flux measurements at the surface of the two materials. The video included audio with subtitles to guide them through the process. Screen shots of this video are provided in Figure 7. With this method, the students were able to feel the materials while watching the real-time plots without getting concerned with how their data looked. They could then focus on their ideas of why the materials felt different and relate that to the graphs of recorded heat flux and temperature. An additional video showed the same experiment being performed but split screened with an infrared camera for the students to see the temperature profiles of the two plates after the hands were placed on them.

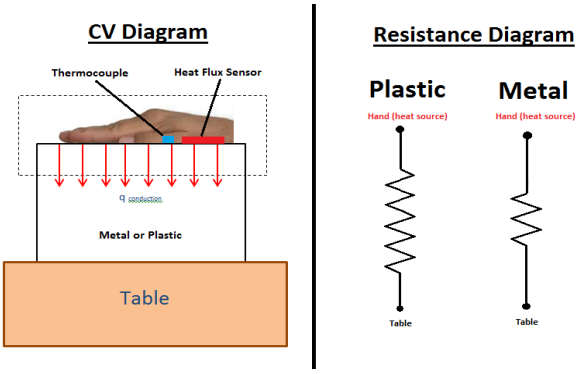


Figure 6: Control volume and thermal resistance diagrams for the first workshop to help the students relate their experiment to problems they solve on tests and for homework

Figure 7 a) (left): Workshop video showing plots of heat flux over time for the two plates
b) (right): The same video showing the experiment under the thermal camera.

The last step was a reflection step where the students were asked questions to help them think about what they did. During the workshop, a single setup of the experiment was placed in the front of the room and all of the students were required to go up and feel the materials and repeat what was performed in the video without actually taking the data.

2.6.1.4 Workshop 2 in Detail

The second workshop, same as the previous year, focused on the topic of fins. At their workstations, the students were provided with a metal fin heated at its base by a resistance heater.

Once again, the first step involved having the students generate ideas and form a hypothesis to answer the challenge question. In addition to the questions asked in the previous year, the restructured workshop featured blank plots of temperature and heat flux and the students were asked to sketch what they predicted the distribution would look like down the fin for the different air speeds. Sketches are important for conceptual understanding because they provide a physical representation of how heat flux and temperature are changing in a situation.

In the next step, a diagram of the physical setup was also added for the students to see how conduction and convection were taking place in the fin. More focus was placed on the physical setup and how heat transfer was physically taking place in the restructured workshops. The diagram the students were provided with is shown in Figure 8. For the experimental procedure, instead of having the students record the data themselves, a video was provided showing the fan blowing air across the fin and the plots showing heat flux and temperature measurements down its length. A split screen in the video showed both plots growing with time after the base heater was turned on as well as what the experiment looked like under the thermal camera. A screen shot of this part of the video is shown in Figure 9. The students were told to feel the temperature distribution down the length of the fin while watching the video so as to keep the students engaged with hands-on activity.

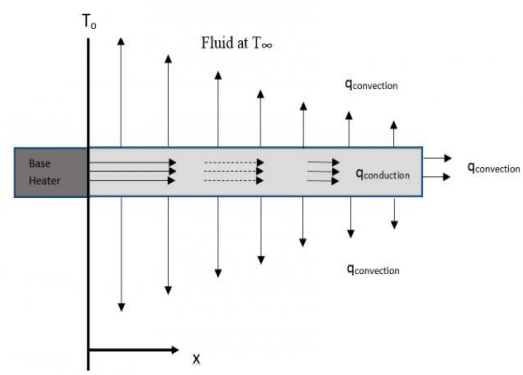


Figure 8: Diagram of fin including how conduction and convection take place homework

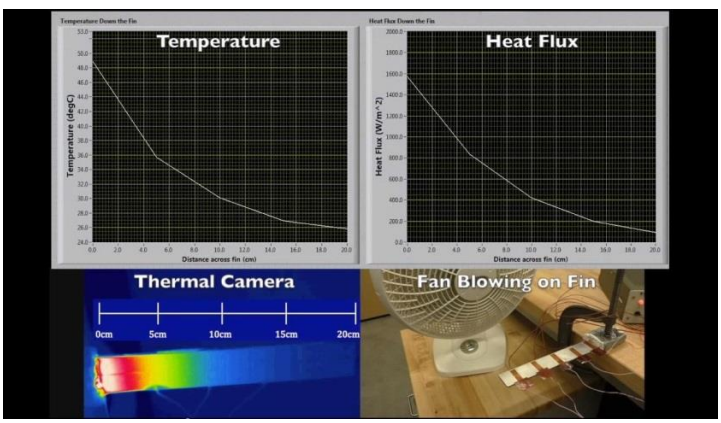


Figure 9: Screen shot of fin video provided to students.

2.6.2 Assessment Methodology

Just as in the previous year, two sections of the junior level heat transfer course were used for analysis. Both sections were taught back-to-back with the same instructor using the same quizzes and tests. The second class was given traditional lectures and was used as the

control group consisting of 69 students, while the first class was the experimental section consisting of 65 students which was given the same lectures along with the six hands-on workshops. Instead of having a workshop every week like in the first year, a workshop was taught every two to three weeks throughout the semester. It took the place of one of the homework assignments to keep the same required workload. To gauge the progress of the students' conceptual understanding for both the experimental and control groups throughout the semester, certain concept-specific questions were also given on tests and quizzes during the course. The questions always had to do with concepts from a specific workshop and were asked on quizzes the week after said workshop was performed. The two mid-term tests both consisted of 5 concept questions similar to those asked on the quizzes.

As a final evaluation, instead of giving a stand-alone concept quiz at the end of the semester like in the previous year, 10 concept questions were given on the final exam. These questions included a few from the previous year's 19 question concept test as well as new questions more focused on concepts specific to the course topics and workshops.

2.6.3 Results and Discussion

Just as in the previous semester, an initial concept inventory quiz given at the beginning of the course was used to establish equality between the sections. Results showed that the two sections were nearly equal in terms of their misconceptions. The average scores on the six-question quiz were 51.3±3.26% correct for the control and 47.4±3.14% correct for the experimental group yielding a p-value of 0.4 with an alpha value of 0.05. Since both sections had been given roughly equal exposure to heat transfer concepts from previous classes, there was no reason to suspect one section to have a better understanding of these concepts than the other.

2.6.3.1 Concept Questions on Quizzes and Tests

Quizzes 3, 6, 7, and 11 all had at least one concept-specific question relating to the topic being taught in class and therefore in the workshops as well. Each quiz was taken 3-4 days after the workshop on that specific quiz topic was performed. Results from all of these quizzes are shown in Table 6. This table provides the quiz topic (same as the workshop topic from the previous week), the scores on the concept specific questions, and the p-values (α=.05). None of the concept specific questions on the quizzes yielded statistically significant differences between the groups.

Table 6: Scores on concept-specific questions from quizzes throughout semester

Quiz Number and Topic	Concept/ Question	Control Score ± SE (%)	Experimental Score ± SE (%)	P-Values
3. Fins	Heat Transfer Coefficient	80.0±4.99	69.0±6.13	0.1265
	Fin Length	84.1±4.64	86.2±4.57	0.7478
6. External Flow	Sketch Heat Flux From a Surface	61.9±6.17	72.7±6.06	0.2108
7. Internal Flow	Plot Temperature Profiles	25.4±5.53	39.7±6.48	0.0932
11. Radiation	View Factor Effects	50.8±6.35	56.9±6.56	0.5010

The third quiz on fins was the first to include concept-specific questions, shown in Table 7. A portion of the second workshop had a hands-on demonstration of the effects of changing the heat transfer coefficient on a fin.

Table 7: Concept questions given on the third quiz to test basic conceptual understanding of fins.

Indicate what would happen to the fin efficiency and fin heat transfer of an individual fin initially having a fin efficiency of 70% (increase, decrease, or no effect) if:		
	Fin efficiency	Fin heat transfer
a) convective heat transfer coefficient is increased	(Ans: Decrease)	(Ans: Increase)
b) the fin length is increased	(Ans: Decrease)	(Ans: Increase)

One of the best ways to gauge conceptual knowledge is through questions that require students to provide plots and sketches of what is happening. The quiz on external flow about halfway through the semester had a question that asked students to sketch the surface heat flux as a

function of x down the length of a surface with air blowing across it. The next quiz on internal flow had a similar question asking students to provide plots of fluid and wall temperature down the length of a tube with a constant heat flux around the outside.

Looking at the two tests that were given, 5 concept questions were given as the first 5 problems on each. For the first test, the only significant difference in scores came from the first question. Both of the first two questions were the same as those from the initial concept quiz. These questions are displayed in Table 8 with their results shown right below in Table 9. The p-values correspond to the test question results. The questions explore the thermal response of materials with different thermal conductivities. The principle is that heat flux increases with thermal conductivity, but the corresponding surface temperature response is less. The first question focuses on the temperature change at the surface of a material. The experimental group yielded a 64.4% improvement on this question compared to a 12.5% improvement by the control group. The second question is about the heat flux at the surface of the material with a 19.4% improvement by the experimental group compared to a 6.2% for the control group. This student performance can be attributed to the fact that resistance diagrams and concepts of thermal resistance were stressed on all of the workshops throughout the semester.

Table 8: First two concept-specific questions from the first test

1. Two solid materials of identical size are sitting at room temperature. One has a low thermal conductivity (insulation) and the other has a high thermal conductivity (metal). Indicate the relative thermal responses between the two materials when the same heat source is placed on each. Which has the faster temperature rise at the surface? a) The low conductivity material b) The high conductivity material c) The two materials respond at the same rate
2. Under the same conditions as question 1, which has a higher rate of heat flux at the surface? a) The low conductivity material b) The high conductivity material c) The two materials respond the same

Table 9: Results from the first two concept questions (Percent of Students with Correct Answers)

Question Number	Section	Results from Initial Quiz ± SE (%)	Results from First Test ± SE (%)	P-Values
1	Control	7.94±3.43	20.6±5.14	0.0001
	Experimental	8.62±3.72	72.3±5.92	
2	Control	74.6±5.53	81.0±4.99	0.2889
	Experimental	69.0±6.13	87.9±4.31	

Table 10 shows the remaining three concept questions that appeared on the first test. Questions 3 and 4 also stressed the concept of heat vs. temperature with question 4 being the only one that yielded a statistically significant difference between the two groups using an alpha value of 0.05. The application, however, is more complicated than the first two questions because now convection has been added. As convection is increased, the thermal resistance is decreased. Most of the students understood that this will decrease the overall resistance of the wall and increase heat flux, as evidenced by the scores in Table 11. The fact that this also decreases the temperature difference between the inside surface of the wall and the room temperature (which means the wall surface temperature is higher) was a lot less obvious to the students as shown by the scores for question 3. This is the one question on which the experimental group did not outperform the control group. The same principle is involved as the first two questions, but the added complexity clearly makes it difficult for many students to extend this concept to a more involved situation.

For the fifth question on the test, students were asked to sketch plots of the temperature and heat flux for a straight fin. While the experimental group once again showed higher scores on both parts of this question, they still seemed to struggle with the underlying concept.

Table 10: The last three concept questions of the first test

3. Consider the wall of a house on a cold day. The inside of the house is warm. The conditions are the same for Case A and Case B except that the heat transfer coefficient on the inside surface of the wall is higher for case A than case B. Which is true under steady-state conditions? a. The inside surface temperature of the wall is higher for Case A than Case B. b. The inside surface temperature of the wall is higher for Case B than Case A. c. There is no difference in surface temperature.
4. Under the same conditions as question 3, which of the following is true? a. The heat flux through the wall is higher for Case A than Case B. b. The heat flux through the wall is higher for Case B than Case A. c. There is no difference in heat flux through the wall.
5. A "straight" fin is mounted onto a wall that is maintained at 0°C. It has a convective heat transfer coefficient with the surrounding air of 10 W/m^2-K at a temperature of 100°C. Neglect radiation and convection from the fin tip. Sketch the temperature and convective heat flux (to the fin) over it's length from $x = 0$ to $x = L$ when the fin efficiency is 60%. Approximate the correct limiting values.

Table 11: Results from the last three concept questions on the first test

Question Number	Control Scores ± SE (%)	Experimental Scores ± SE (%)	P-Values
3	39.7±6.21	24.1± 5.67	0.0661
4	58.7±6.25	82.8±5.00	0.0034
5 (Temperature)	71.4±5.74	84.5±4.80	0.0822
5 (Heat Flux)	9.52±3.73	22.4±5.52	0.0498

The second test had a similar format as the first with a set of five concept questions provided as the first of five problems. The questions are shown below in Table 12 and the results are shown in Table 13. Unlike on the first test, the experimental group scored worse than the control group on 4 out of the 5 concept questions and statistically significantly worse on question two using an alpha value of 0.05. It is possible that for this question, the workshop students confused themselves by thinking about the workshop which involved hot air flowing

through a room temperature tube while the concept question involves a heated tube. What's particularly interesting from these results, however, is the lack of better scores by the experimental group, especially on questions 3 and 4. The 3rd workshop on external flow involved having both thick and thin heated plates in front of the students and a fan to blow cool air across them. The teaching assistant even made sure that each student got their hands on the plates to feel the different surface temperatures as they watched the videos. The results from these questions seem to suggest that the videos had almost no effect on the students' ability to answer this basic question on external flow.

Table 12: Concept questions given as problem 1 on test 2

1. For internal flow through a channel with constant wall temperature that is higher than the fluid temperature, how will the outlet fluid temperature change if the specific heat of the fluid is increased while all other flow properties are the same? a) Increase b) Decrease c) Remains the same
2. For internal flow through a channel with a constant wall temperature that is higher than the fluid temperature, how will the overall heat transfer change if the specific heat of the fluid is increased while all other flow properties are the same? a) Increase b) Decrease c) Remains the same
3. For laminar external flow parallel to a constant heat flux flat plate, how does the surface temperature vary along the plate? a) Increases with distance b) Decreases with distance c) There is no difference in surface temperature along the plate
4. Mark all of the correct reasons for your answer to number 3 a) The heat transfer coefficient is constant. b) The boundary layer thickness increases with distance along the plate. c) The heat transfer coefficient decreases with distance along the plate. d) The heat transfer coefficient increases with distance along the plate. e) The boundary layer thickness is constant. f) The heat flux is constant so the temperature difference has to be constant.
5. If the diameter of a heated cylinder is increased, what is the impact on the heat flux from the exterior of the cylinder? Assume that the exterior fluid velocity (in crossflow) and all properties are the same and the cylinder temperature is the same. a) Heat flux increases b) Heat flux decreases c) Heat flux remains the same

Table 13: Results from test 2 concept questions

Question Number	Control Scores ± SE (%)	Experimental Scores ± SE (%)	P-Values
1	77.8±5.48	67.2± 6.22	0.1933
2	85.7±4.44	65.5±6.30	0.0088
3	63.5±6.11	53.4±6.61	0.2621
4	50.8±6.35	60.3±6.48	0.2905
5	55.6±6.31	53.4±6.61	0.8161

2.6.3.2 Final Exam Concept Questions

At the end of the semester, ten concept questions were given on the final exam for both the experimental and control groups. One question (question 5) was removed, however, due to ambiguity in its answer choices. The nine remaining questions tested all six of the critical heat transfer concepts. Of the nine questions, one was focused on the topic of radiation, two were about internal flow, and six focused on ideas of thermal resistance and the difference between heat and temperature: the crux of the course. All nine of these questions are displayed in the appendix. The question on radiation (question 1) was the only one that showed a statistically significant difference between the groups. The results from this question, along with the average scores of the nine questions total are shown in Table 14. A bar chart of all of the questions is displayed in Figure 10.

Table 14: Average scores on question 1 and overall for final exam concept questions (question 1 was the only one that yielded a statistically significant difference)

	Control Scores ± SE (%)	Experimental Scores ± SE (%)	P-Values
Question 1	63.5±6.11	82.1±5.16	0.0217
Total Scores	63.8±1.94	66.8±2.10	0.3655

Unlike the previous semester, the average scores on the final concept assessment was not significantly higher than the control group as seen from the averages and p-value. Even on questions geared to specifically target ideas in the workshops, the experimental group did not outperform the control group. As mentioned, six questions were on thermal resistance. Of these 6 questions, 4 referred to a figure showing a diagram exactly like one of their workshops. It

involved sandwiching a heater between a metal and plastic plate, both exposed to convection. The questions asked about the relative values of heat flux and temperature through the plates as well as reasons to justify their answers. In the workshop, the students were given that exact setup and allowed to feel the relative temperatures of the plates. The video showed them the relative heat flux and temperature values for this situation, as well as what would happen if more thermal resistance was added to both the plates. As indicated by the results in Table 14 and Figure 10, it seems that this workshop, as well as all of the other ones, had no effect on the students' performance and conceptual understanding.

One reason for this could be attributed to the fact that the videos placed the students in a passive state of mind. In the first year, the students were forced to use the data acquisition software, take the data, and perform the experiment. Their data directly reflected how well they performed the experiment. This cause and effect method forced the students to think more about the plots and data being displayed in real time. If they made a mistake in the experiment, they would be forced to think about why certain heat flux or temperature values didn't look right, thinking back to the underlying concepts. In the second semester, the videos were more or less mistake free. The cause and effect structure was removed since the students were no longer taking the data. They just passively watched the videos as if they were just another lecture. This passive mindset disengaged the students and took away from the whole hands-on experience. On the other hand, forcing the students to take the data forces them to also be engaged in the experience and think about the concepts more.

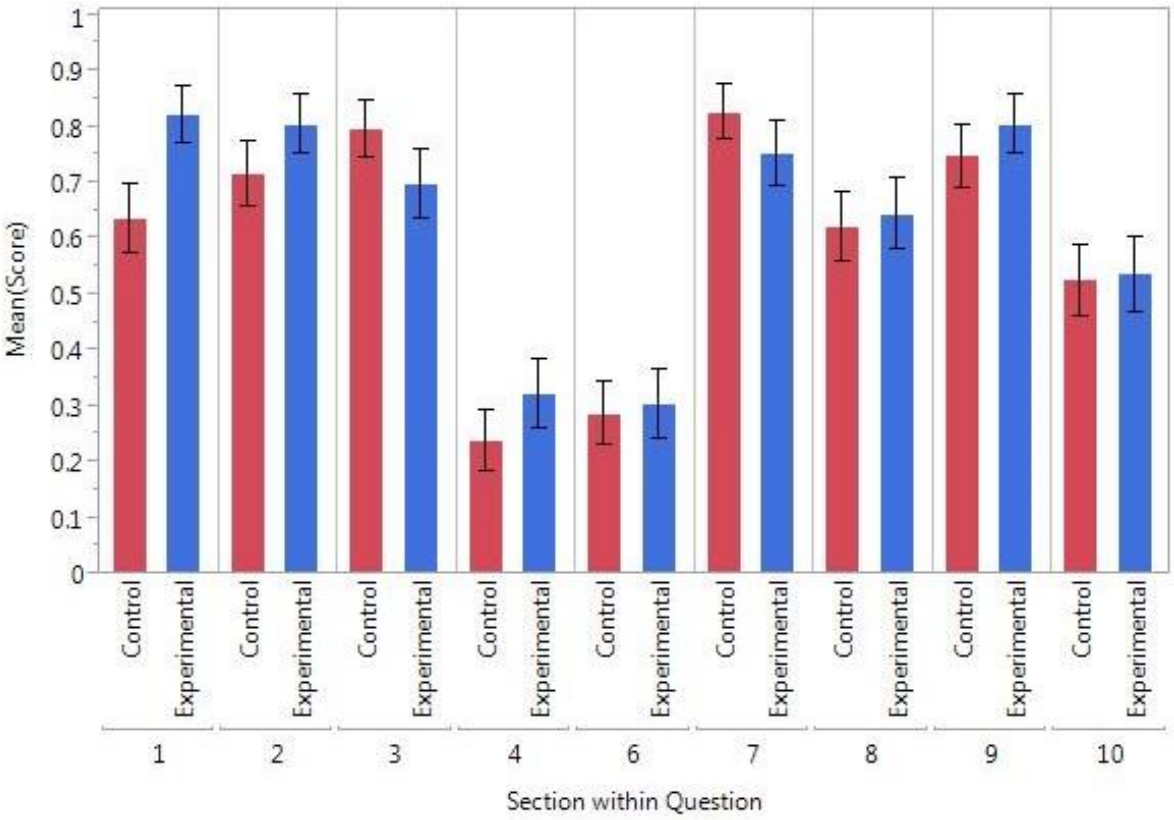


Figure 10: Results from concept questions on final exam.

2.6.3.3. Surveys

Aside from the concept questions, just as in the first year, a survey was given to the students to gauge the benefit of the workshops from a qualitative standpoint. The survey asked 15 short answer and yes or no questions focused on how the students in the experimental section liked the workshops and if they believed the workshops helped them in their understanding of the concepts. 16 students from the experimental section took this particular survey. Of those 16 students, 15 students mentioned that the workshops were helpful in understanding the material, 5 believed they learned the concepts better in the during the actual workshop than the lecture, 12 believed the workshop sessions contributed significantly to their understanding of heat transfer concepts, 13 believed the hands-on nature of the workshops contributed significantly to their learning of the concepts, and 14 would recommend the workshops be offered to future versions

of the class. So while the results from the concept questions reveal otherwise, the students believed that the workshops were beneficial to their understanding of the difficult concepts. This is worth noting because it is possible that the workshops have intrinsic value that can't easily be measured quantitatively. While the students' problem solving skills can be assessed through textbook test problems linking to their homework and examples in class, conceptual understanding is much harder to assess. It is possible that the concept questions or even the concepts themselves don't reflect how students think about heat and temperature.

2.6.4 Conclusions

The addition of hands-on workshops for undergraduate students in Mechanical Engineering heat transfer classes has been demonstrated to improve their conceptual understanding of the material only if they are forced to engage and think about the experiment being performed. The introduction of video-enhanced instruction ended up yielding the opposite effects of what was originally hypothesized. It was hypothesized that by not worrying about how they performed the experiment and tinkering with the data acquisition equipment, the students would be able to focus more on the underlying concepts. Results from this study show that the opposite may be true. By passively watching videos, the students become disengaged from the hands-on aspect of the workshops, which makes the workshops seem more like a lecture. Taking the data forces the students to engage in the experiment and think more about why the data turns out the way it does. The way the students perform the experiment has a direct effect on their results. Results show the experimental group out-performed the control group in the first semester, but not the second.

Future work should entail going back to the first semester workshop format but also thinking more about the underlying concepts and how to assess conceptual understanding. As

seen from survey results, the students believed they understood the concepts better even though the concept question results reveal otherwise. A study in student cognition of conceptual understanding and how to assess it should be performed. It is possible that feeling heat transfer and performing experiments has intrinsic value that goes beyond results to multiple choice concept questions. Future work should also entail trying to combine conceptual understanding with problem-solving skills. The workshops will continue to be modified to better relate them to typical problems the students see on homework, tests, and quizzes. A study will also be performed on how to convey concepts in order to help the students retain them even after they have finished taking the class.

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2.8 References

1. Nottis, K. E. K., M. Prince, M. Vigenat, S. Nelson, and K. Hartsock, 2009, "Undergraduate Student's Understanding of Heat, Temperature and Radiation," *Northeastern Educational Research Association Annual Conference Proceedings*.

2. Prince, M. J. and R. M. Felder, "Inductive Teaching and Learning Methods: Definitions, Comparisons, and Research Bases," *Journal of Engineering Education*, Vol. 95, No. 2, pp. 123-138, (2006).

3. Wankat, P. and F. Oreovicz, *Teaching Engineering*, McGraw-Hill, New York, (1993).

4. Miller, R.L., R. A. Streveler, and B. M. Olds, 2007, "Use of Concept Inventories to Identify Misconceptions in Thermal Sciences," *Proceedings of the 2nd International Conference on Engineering Education & Training*, Kuwait City, Kuwait, April 9-11.

5. Self, B. P., R. L. Miller, A. Kean, T. J. Moore, T. Ogletree, and F. Schrieber, 2008, "Important Student Misconceptions in Mechanics and Thermal Science: Identification using Model-eliciting Activities," *ASEE/IEEE Frontiers in Education Conference*, Saratoga Springs, NY.

6. Jacobi, A., J. K. Martin, J. Mitchell, and T. Newell, 2003, "A Concept Inventory for Heat Transfer," *Proceedings Frontiers in Education Conference*, Boulder CO, USA.

7. Streveler, R. A., R. L. Miller, M. A. Nelson, M. R. Geist, and B. M. Olds, 2008a, "Developing an Instrument to Measure Engineering Students Misconceptions in Thermal and Transport Science," *Journal of Engineering Education*.

8. Miller, R. L., R.A. Streveler, B.M. Olds, M.T.H. Chi, M.A. Nelson, and M.R. Geist, 2006, "Misconceptions about Rate Processes: Preliminary Evidence for the Importance of Emergent Conceptual Schemas in Thermal and Transport Sciences," *Proceedings of the American Society for Engineering Education Annual Conference*, Chicago, Illinois, June 18-21.

9. Streveler, R. A., Litzinger, T. A., Miller, R. L., and Steif, P. S., 2008b, "Learning Conceptual Knowledge in the Engineering Sciences: Overview and Future Research Directions," Journal of Engineering Education, Vol. 98, pp. 279-294.

10. Bransford, J.D., A. L. Brown, and R. R. Cocking, eds., 2000, *How People Learn: Brain, Mind, Experience, and School*. National Academy Press, Washington, D.C.

11. Pellegrino, J.W., 2006, "Rethinking and redesigning curriculum, instruction and assessment: What contemporary research and theory suggests." A paper commissioned by the National Center on Education and the Economy for the New Commission on the Skills of the American Workforce.

12. Albanese, M. A. and S. Mitchell, 1993, "Problem-Based Learning: A Review of Literature on its Outcomes and Implementation Issues," *Academic Medicine*, Vol. 68, pp. 52-81.

13. Vanderbilt University, accessed 2009, "Star Legacy Modules," Iris Center for Faculty Enhancement, http://iris.peabody.vanderbilt.edu/hpl/chalcycle.htm.

14. Barr, R., M. Pandy, A. Petrosino, R. Roselli, S. Brophy, and R. Freeman. 2007. Challenge-based instruction: The VaNTH biomechanics modules. *Advances in Engineering Education* 1 (1): 1-30.

15. Roselli, R.J. and S.P. Brophy, 2003, Redesigning a biomechanics course using challenge-based instruction. *IEEE Engineering in Medicine and Biology Magazine* 22 (4): 66–70.

16. Martin, T., S. D. Rivale, and K. R. Diller, 2007, "Comparison of Student Learning in Challenge-based and Traditional Instruction in Biomedical Engineering," *Annals of Biomedical Engineering*., Vol. 35, pp. 1312-23.

17. Rayne, K., T. Martin, S. Brophy, N.J. Kemp, J.D. Hart, and K.R. Diller. 2006. The development of adaptive expertise in biomedical engineering ethics. *Journal of Engineering Education* 95 (2): 165- 173.

18. Cordray, D. S., T. R. Harris, and S. Klein, 2009, "A Research Synthesis of the Effectiveness, Replicability, and Generality of the VaNTH Challenge-based Instructional Modules in Bioengineering," J. Eng. Education, Vol. 98, pp. 335-348.

19. Roselli, R.J. and S.P. Brophy, 2006, Effectiveness of challenge-based instruction in biomechanics. *Journal of Engineering Education* 95 (4): 311-324.

20. Prince, M. J. and M. Vigeant, 2006, "Using Inquiry-based Activities to Promote Understanding of Critical Engineering Concepts," *ASEE Annual Conference*, 2006-1379, Chicago, IL.

21. Nottis, K. E. K., M. J. Prince, and M. A. Vigeant, 2009, "Building an understanding of heat transfer concepts in undergraduate chemical engineering courses," *US-China Education Review*, Vol. 7, No. 2, pp. 1-9.

22. Golter, P.B., Van Wie, B.J., Scuderi, P.V., Henderson, T. W., Dueben, R. ., Brown, G.R., and Thomson, 2005, W. J., "Combining Modern Learning Pedagogies in Fluid Mechanics and Heat Transfer, "*Chemical Engineering Education*, Vol. 39, pp. 280-287.

23. Van Wie, B. J., Poshusta, J. C., Greenelee, R. D., Brereton, R. A., 1994, " Fun Ways to Learn Fluid Mechanics and Heat Transfer," *Chemical Engineering Education*, Vol. 28, pp. 188-192.

24. Minerick, A., 2009, "A Desktop Experiment Module: Heat Transfer," *ASEE 2009 Annual Conference*, Austin, TX.

25. Abdul, B., Shide, E., Bako, R., Golter, P., Babauta, J., Van Wie, B., and Brown, G., 2009, "An evaluation of Pedagogical Gains in a Fluid Flow Class When Using Desktop Learning Modules in an African University," *ASEE 2009 Annual Conference*, Honolulu, HW, AC 2009-1122.

26. Millard, D., Choulikha, M., Berry, F., 2007, "Improving Student Intuition via Rensselaer's New Mobile Studio Pedagogy," *ASEE 2007 Annual Conference*, Honolulu, HW, June.

27. Belcher, J., Dourmashkin, P. and Dori, Y., 2004, "Technology Enabled Active Learning (TEAL): Studio Physics at MIT," http://gallery.carnegiefoundation.org/collections/keep/jbelcher.

28. Clark, R., Jr., Flowers, G. H., Doolittle, P., Meehan, K., and Hendricks, R. W., 2009, "Work in Progress – Transitioning Lab-in-a-Box (LiaB0 to the Community College Setting," *39th ASEE/IEEE Frontiers in Education Conference*, San Antonio, TX.

Chapter 3 – Conclusions and Recommendations

3.1 Conclusions

The conceptual knowledge of heat transfer students was significantly improved during the first year of the study involving the hands-on workshops, but not as much in the second year. It appears that even though the students were able to feel the experiments and watch pre-recorded videos to simulate real time data, they were unable to improve on their conceptual knowledge as well. Students really need to be forced to perform the actual experiment and record the data themselves in order to truly understand the concepts. There seems to be intrinsic value in actively doing the experiment. The more active an experiment is, the more students benefit from it. The workshops should also continue to be given the week prior to the material being taught in lecture. Many misconceptions seem to come from sitting in the lecture and just looking at equations without knowing what is physically happening. Being able to see and touch a physical setup of a topic really helps to link concepts and equations.

Looking beyond the concept questions, the students' problem solving skills lacked improvement from the workshops. The students were unable to link the concepts they learned to the problems they had to solve on tests and quizzes. This may be in part due to the nature of how the class is taught. Completely separating the lecture and discussion of equations from the workshops may make it difficult for students to link concepts with application of the concepts.

Although the workshops showed little improvement with the students' problem solving skills, surveys reveal that the students believed otherwise. They thought the workshops gave them a real-world feel of the concepts and thus helped them in all aspects of the course. They particularly liked being able to actually see what they learned in lecture much like they can in other classes and preferred having the workshops as part of the course over not having them.

This is worth noting because it shows that the students are excited when they walk into the workshop and enjoy them just like any other lab class. While subjects like robotics are easy for the students to get excited about because of their intrinsic hands-on nature, this was one of the first times heat transfer was presented in such a way as to motivate students to physically participate in such an abstract subject.

Although the workshops were created using easily available materials and components, currently procured heat flux sensors are very expensive. Research is being done to mass-manufacture such sensors to make them available to students all over the country. Future work should work to push forward the workshops and sensors to be used in mechanical engineering departments throughout the country.

The workshops should also continue to be revised so as to link the concepts more to problems the students see on homework and tests and what they are taught in their lectures. The second semester of workshops started using control volume and resistance diagrams to help the students link every experiment to ideas of thermal resistance and the necessity of using a control volume for analysis. This should be expanded to include problem-like scenarios on the workshops where the students are given a problem such as they might see on a quiz or test, perform an experiment that directly links to that problem, and then solve the problem using the data and information they collected from the experiment.

Appendix A: First Semester Workshops

Workshop 1

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #1:

TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

THE CHALLENGE

Objective:

- Learn how to use sensors and data-acquisition instruments to take measurements of temperature and heat flux.
- Gain an understanding of the difference between heat, energy, and temperature.
- Gain an understanding of how to determine thermal properties of a material.
- Gain an understanding of the difference between heat flux and temperature measurements.

Challenge:

You are the lead engineer working for *NovaMaterials*, an engineering firm specializing in heat transfer research.

One of your clients recently shipped two material samples to your team for evaluation. These material samples are going to be used as a thermal barrier in a hydrogen fuel-cell automobile.

Your client knows very little about the materials, and has asked for your help in identifying their thermal properties. Specifically, answer the following challenge question:

Challenge Question:

Which material is more thermally conductive?

Available Equipment:

In your laboratory, you have access to

- a *temperature sensor* (a surface mount thermocouple)
- a *heat flux sensor*
- an *electric heater* that is mounted on a piece of insulation. The heater is set to run continuously.

Both sensors are connected to a *data acquisition unit* (DAQ) that will record the results of the measurements taken from the two sensors.

Design an experiment wherein your team uses these tools to determine the relative thermal conductivity of the two materials

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #1:

TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 1: GENERATE IDEAS

The goal of this phase is to establish your experimental plan to answer the Challenge Question. As a team, discuss the following questions; use the answers to help motivate your strategy.

- What is the difference between temperature and heat flux?

- How could measurements of temperature and heat flux assist you in determining the thermal conductivity of these two materials?

Next, frame your **hypothesis**: (write your answers in the spaces below)

- How do you expect thermal conductivity to affect the measured temperature and heat flux of your samples?

- What is your basis for this hypothesis?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #1:

TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 2: GATHERING PERSPECTIVES AND RESOURCES &

STEP 3: RESEARCH AND REVISE

- Consult the following information as needed.
- Refine your planned experimental procedure as needed.
- Consult the "Tips for Getting Started" section

Review of Fourier's Law and Thermal Conductivity:

For heat conduction, the rate equation is known as Fourier's law. For a one-dimensional plane wall having a temperature distribution *T(x)*, the rate equation is expressed as:

$$q'' = -k\left(\frac{dT}{dx}\right)$$

- The heat flux, q'' (W/m^2) is the heat transfer rate in the *x* direction per unit area perpendicular to the direction of transfer. It is proportional to the temperature gradient, *dT/dx*, in this direction.
- The proportionality constant, *k*, is a transport property known as the thermal conductivity (W/mK). It is a material property.

Tips for Applying/Removing the Sensors:

- Both the thermocouple and the heat flux sensor are very fragile; Handle them carefully.
- When removing the sensors from a material surface, pinch the wire down as you remove any tape (to support the connection between the wire and the sensor, which is susceptible to fatigue).

Suggestions for Getting Started (**EXPERIMENTAL SESSION #1):**

- Use the sensors to identify the difference between temperature and heat flux.

- Collect heat and temperature data with the sensors and DAQ while:
  - Holding the heat flux sensor and temperature sensors in your hand (remember to be careful with the sensors; DO NOT bend them!)
  - Placing the sensors on a variety of materials around you (try them on the heater, the insulation, the two materials, etc.)
  - Try turning the heat flux sensor over – what is different about the measurement?

- By comparing the results of these trials, determine what these two sensors are measuring.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #1:

TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 2: GATHERING PERSPECTIVES AND RESOURCES &

STEP 3: RESEARCH AND REVISE

Research and Revise

- Once you have an understanding of how the sensors work, and what information they are capturing, refine your experimental plan as needed.
- Provide a Schematic of how your team plans to set up your experiment (label the temperature and heat flux sensors and material sample) in order to answer the Challenge Question. Use a pencil so that you can revise as necessary

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #1:

TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 4: TEST YOUR METTLE

Use the provided insulation and heater in conjunction with the sensors and the two different materials to characterize the thermal response of the materials.

- **EXPERIMENTAL SESSION #2:**
  - Evaluate the thermal conductivity of the polymer
    - Orient the sensors and metal sample as your group has planned.
    - Use the DAQ (and associated Labview and Matlab programs) to collect the data.
  - Evaluate the thermal response of the metal.
    - Orient the sensors and use the DAQ to collect data.
    - Print the resulting plots
  - When you are done, disassemble your experiment before the next group arrives at the station

As you work towards answering the Challenge Question, answer the following questions:

1. Are the tests that you are conducting transient or steady-state? How do you know?

2. What are the relative values of temperature change and heat flux for the two materials?

3. What can you tell about the relative thermal conductivity of the two materials? How?

4. Attach and label (at least) four graphs of the temperature and heat flux combinations (i.e., temperature and heat flux as function of time for each material).

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #1:

TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 5: REFLECTION

Discuss and answer the following questions:

1. What different information is provided by the heat flux versus the temperature measurements?

2. Did your results agree with your hypothesis from Step 1? Why or why not?

3. What did you learn? What do you know now, that you didn't know before?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #1:

TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

USING THE DAQ

EXPERIMENTAL SESSION #1:

- On the laptop, open the appropriate folder ("Group 1" or "Group 2" in the workshop folder on the Desktop)
- Select either of the Labview programs ("Metal" or "Plastic") in the Desktop/Workshops/Workshop_1/Group# folder
- Press "Run" button (at top left) to collect 20 seconds of data.
- For this session, the data will not be saved so press the run button as many times as necessary to see how the sensors behave

EXPERIMENTAL SESSION #2:

- Orient the sensors and plastic sample as your group has planned
- Select the Labview program "Plastic" in the Desktop/Workshops/Workshop_1/Group# folder
- Start collecting data by clicking the "Run" button
    - Sensor data is automatically saved to the "Input_Data" folder
- To analyze the data, open the "Output_Plots" folder (Desktop/Workshops/Workshop_1/Group#/Output_Plots)
- Select the Matlab m-file "Workshop_1_Plots.m"
- In Matlab, click "Run" (the "Play" button)
- Enter your computer number, 1-5 (your number is written on the laptop)
- Enter your group number (1 or 2)
- Print the resulting plots
    - File → Print
    - Choose "HP Laserjet 400"
- Repeat the procedure for the metal sample
    - Select the Labview program "Metal" in the Desktop/Workshops/Workshop_1/Group# folder
- When you are done, disassemble your experiment before the next Group arrives at the station

Workshop 2

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #2:
EXTENDED SURFACES (FINS)

THE CHALLENGE

Objective:

- Learn how fins affect heat transfer.
- Learn how convection flow affects fin performance.
- Learn how to measure the convection heat transfer coefficient.
- Gain an understanding of the difference between heat, energy, and temperature.
- Gain an understanding of the difference between heat flux and temperature measurements.

Challenge:

You are the lead thermal engineer working for *PowerElectronics*, an engineering firm specializing in the design and manufacture of high-power, portable energy devices.

Your colleague, a mechanical designer, has asked for your help in specifying extended surfaces (fins) for a new device to help with thermal management issues in the design.

Specifically, you are asked to determine the convection heat transfer coefficient for the designed fin at two different wind conditions (low and high speeds).

Challenge Questions:

- ***What is the convection coefficient and overall heat transfer for the specified fin at two different wind conditions?***
- ***What is the efficiency of the fin?***

Available Equipment:

Your experimental setup is composed of:

- A straight *fin* of uniform cross section has been attached to the lab table. The is 23.5 cm long, 3.7 cm wide, and 0.48 cm thick.
- A *heater* is located at the base of the fin.
- Five (5) *temperature sensors* (surface mount thermocouples) have been placed along the length of the fin. One at the heater (x=0), and four along evenly spaced along its length (5 cm, 10 cm, 15 cm, and 20 cm).
- An additional *temperature sensor* is present to capture the temperature of the surrounding air.
- A *heat flux sensor* (not mounted)

All of the sensors are connected to a *data acquisition unit* (DAQ), which will record the results measurements during experimentation.

Use these tools to determine the convection coefficient and temperature distribution at two fan speeds.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #2:
EXTENDED SURFACES (FINS)

STEP 1: GENERATE IDEAS

The goal of this phase is to establish your experimental plan to answer the Challenge Questions. As a team, discuss the following questions; use the answers to help motivate your strategy.

- Identify where conduction and convection takes place on the fin.

- How does the thermal energy transfer from the heater to the air?

- How could measurements of temperature and heat flux assist you in determining the convection coefficient over an extended surface?

Next, frame your **hypothesis**: (write your answers in the spaces below)

- How will the convection coefficient change between the two fan settings?

- Will the net heat transfer increase or decrease?

- What is your basis for your hypotheses?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #2:
EXTENDED SURFACES (FINS)

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH & REVISE

- Consult the following information as needed.
- Refine your planned experimental procedure as needed.
- Consult the "Tips for Getting Started" section

Review of Newton's Law of Cooling and the Convection Coefficient:

For heat convection, the rate equation is known as Newton's Law of Cooling. The rate equation is expressed as:

$$q'' = h(T_S - T_\infty)$$

The convective heat flux, q'' (W/m^2) is proportional to the difference between the surface and fluid temperatures, T_s and T_∞, respectively.

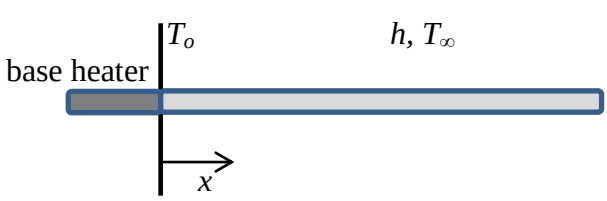
The proportionality constant, h, is termed the convection heat transfer coefficient (W/m^2-K). It depends on conditions in the boundary layer, which are influenced by surface geometry, the nature of the fluid motion, and an assortment of fluid thermodynamic and transport properties. It can be determined at any surface location from heat flux and temperature measurements.

Evaluating Fin Performance

The ultimate goal of a fin is the transfer of thermal energy q_{fin} from a surface to a fluid. The amount of surface area added by the fin is therefore an important aspect of the problem in determining q_{fin}. Note that the temperature distribution along the length of the fin (x-direction) is not uniform. Another important measure of fin performance is the ratio of the fin heat transfer to the heat transfer that would exist if the entire fin was uniform at the base temperature,

$$q_{max} = hA_s(T_o - T_\infty)$$

This ratio is called the fin efficiency, $\eta = q_{fin}/q_{max}$. It relates how efficiently the fin surface transfers heat to the surroundings.



ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #2:
EXTENDED SURFACES (FINS)

STEP 4: TEST YOUR METTLE

Use the provided setup and sensors to conduct your experiments at two different fan conditions. Print plots of the temperature and heat flux distributions for the two fan settings.

Tips for Getting Started:

- The locations of the six thermocouples are fixed. Their position cannot be changed.
- Determining the appropriate location of the heat flux sensor is an important part of this challenge.
    - *Hint*: Think about how *h* is calculated (it is a function of heat flux and a temperature difference)
    - *Hint*: Use your hand to feel the fin temperature to get an idea of where the most convection is taking place.
    - *Hint*: Be sure to use the same heat flux location for both fin conditions.

- **EXPERIMENTAL SESSION #1:** Evaluate the fin performance for wind condition #1
    - Place the heat flux sensor as your group has planned.
    - On the lab laptop, open the appropriate folder (Desktop/Workshops/Workshop_2)
    - Select the Labview program "Low_Fan"
    - Press "Run" button (at top left) to collect 20 seconds of data.
    - Sensor data is automatically saved to the "Input_Data" folder
    - To analyze the data, open the "Output_Plots" folder
    - (Desktop/Workshops/Workshop_2/Output_Plots)
    - Select the Matlab m-file "Low_Fan_Plots.m"
    - In Matlab click "Run" (the "Play" button)
    - Enter your computer number, 1-5 (your number is written on the laptop)
    - Print the resulting plots
    - When you are done, take your heat flux sensor off of the fin
    - Go to a table and analyze the results for this case on the following pages

- **EXPERIMENTAL SESSION #2:** Evaluate the fin performance for wind condition #2
    - Place the heat flux sensor in the same location you did for Session #1
    - Select the Labview program "High_Fan"
    - Start collecting data by clicking the "Run" button
    - Open the "High_Fan.m" Matlab m-file in the "Output Plots" folder
    - In Matlab click "Run" (the "Play" button); Print the resulting plots
    - When you are done, take your heat flux sensor off of the fin
    - Finish analyzing your results for both cases

As you work towards answering the Challenge Question, answer the following questions:

5. What is the surface area of the fin?
   A_s =

6. Does the fin appear to be at steady-state conditions? How do you know?

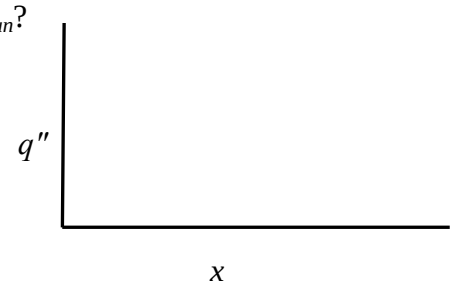
7. Estimate the convection heat transfer coefficient from the heat flux and temperature measurements at the two fan settings:

   - Convection heat transfer coefficient (W/m^{2}K) for Low Fan:

   - Convection heat transfer coefficient (W/m^{2}K) for High Fan:

8. Can you assume that the value of the convection coefficient is constant over the length of the fin?

9. What is the relation between your temperature plot and the heat flux distribution on the fin? Sketch it below. What is the relation between this local heat flux and the total heat transfer, q_{fun}?



10. Estimate both the total heat transfer from the fin q_{fin} and q_{max} using the convection coefficient (h) and the temperature measurements along the fin.

    <u>Low Fan</u>

q_{fin}

q_{max}

<u>High Fan</u>

q_{fin}

q_{max}

11. Calculate the fin efficiencies at both fan speeds.

<u>Low Fan</u>
η

<u>High Fan</u>
η

12. Attach and label plots of the temperature distributions for the two fan settings.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #2:
EXTENDED SURFACES (FINS)

STEP 5: REFLECTION

Discuss and answer the following questions:

4. How does temperature change along the length of the fin?

5. How do changes in *h* affect fin performance?

6. How is the convection coefficient affected by fan speed?

7. Did your results agree with your hypothesis? Why or why not?

8. What did you learn? What do you know now, that you didn't know before?

Workshop 3

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #3:
INTRODUCING TRANSIENT HEAT TRANSFER - CALORIMETERS

THE CHALLENGE

Objective:

- Gain an understanding of transient heat transfer.
- Gain an understanding of how temperature and heat flux change with time.
- Gain an understanding of the difference between heat, energy, and temperature.
- Gain an understanding of the difference between heat flux and temperature measurements.

Context and Challenge:

As a senior engineer in the Thermal Engineering Branch at NASA Ames, one of your responsibilities is to evaluate new technologies for thermal protection of re-entry vehicles. One of the proposed sensors used in the arc-jet facility (for simulating re-entry conditions) uses the rate of temperature change to relate to the heat flux experienced by the test materials. Your task is to determine how to use these measurements.

Challenge Questions:

- ***How should the material respond to heating and cooling events?***
    - ***How should the temperature of the material change over time?***
    - ***How should the heat flux change over time?***

Available Equipment:

Your experimental setup is composed of:

- A piece of the metal that you are evaluating. It is aluminum with a mass of 14 grams, and dimensions of 6.3 cm x 2.5 cm x 0.6 cm.
    - A thermocouple has been mounted inside.
    - A heat flux sensor has been mounted to its surface.
- A container with ice water, to be used to evaluate the material's response to cooling. A thermocouple is submerged in the cold water to measure its temperature.
- An electric hair dryer, to be used to evaluate the material's response to heating. A thermocouple is attached to the hair dryer to measure the temperature of its air flow.
- All of the sensors are connected to a *data acquisition unit* (DAQ), which will record the results measurements during 40-second long tests.

Use these tools to determine the material's transient response to thermal events.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #3:
INTRODUCING TRANSIENT HEAT TRANSFER - CALORIMETERS

STEP 1: GENERATE IDEAS

The goal of this phase is to establish a hypothesis for the expected behavior of the metal. As a team, discuss the following questions.

- Draw the curve you expect for the material's *temperature response* to the *cooling event* as a function of time.

- Draw the curve you expect for the material's *temperature response* to the *heating event* as a function of time.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #3:
INTRODUCING TRANSIENT HEAT TRANSFER - CALORIMETERS

STEP 1: GENERATE IDEAS

- Draw the curve you expect for the material's *heat flux response* to the *cooling event* as a function of time.

- Draw the curve you expect for the material's *heat flux response* to the *heating event* as a function of time.

- What principle can you use to relate the change in temperature over time with the heat flux?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #3:
INTRODUCING TRANSIENT HEAT TRANSFER – CALORIMETERS

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH & REVISE

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

Lumped Capacitance Assumption

The simplest method to model transient heat transfer is to assume that the material under consideration is at a uniform (but not steady) temperature. This often works well for high conductivity materials, such as metals. Specifically this assumption is good whenever the thermal resistance within an object is much less than thermal resistance outside of the object. The changing uniform temperature within the object can then be treated like a capacitative reservoir which absorbs or emits thermal energy according to its mass and specific heat. The energy conservation expressed by the first law of thermodynamics is

$$\left(\frac{dE}{dt}\right)_{system} = \sum q_{in} - \sum q_{out}$$

The rate of change of internal energy in the system is

$$\left(\frac{dE}{dt}\right)_{system} = mC\frac{dT}{dt}$$

The specific heat, C, of the aluminum is approximately C = 900 J/kg-K and the mass of the sample is m = 14 grams.

STEP 3: RESEARCH AND REVISE

- Can you apply the lumped capacitance assumption to your experimental setup? Why or why not?

- How does this affect your hypothesis? Can you apply the energy conservation equation to determine the heat flux from the rate of temperature change?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #3:
INTRODUCING TRANSIENT HEAT TRANSFER – CALORIMETERS

STEP 4: TEST YOUR METTLE

Use the provided setup and sensors to conduct your experiments. Evaluate the material's heat flux and temperature responses over time by collecting heat flux and temperature data during two thermal events (cooling and heating). Print plots of the temperature and heat flux for the two events.

USING THE DAQ

- On the laptop supplied, open the appropriate folder (Desktop/Workshops/Workshop_3)
- Select the appropriate Labview program ("Cooling" or "Heating")
- Press "Run" button (at top left) to collect 40 seconds of data.
- Sensor data is automatically saved to the "Input_Data" folder
- Print a table of your data for each case from the Labview front panel by clicking "file" then "print window"
- To analyze the data, open Desktop/Workshops/Workshop_3/Workshop_3_plots
- In Matlab click "Run" (the "Play" button)
- Enter your computer number, 1-5 (your number is written on the laptop)
- Print the resulting plots
    - Two plots will be printed for each thermal event (heat flux and temperature as a function of time)

EXPERIMENTAL SESSION

- Start with Cooling
    - The exercise will start with the metal at room temperature.
    - Select and start the cooling program to collect temperature and heat flux data for 40 seconds. Once started place the metal in the ice water.
- Then apply Heating
    - Remove the metal from the cold water and quickly dry it.
    - Place the metal on the foam insulation.
    - Set the blow dryer fan on "High" and let it heat up for about 10 seconds.
    - Select and run the heating program to acquire temperature and heat flux data. Then apply the hair dryer directly onto the top of the metal part.
        - Keep the dryer steady; don't move it around the heat flux sensor
        - Keep the dryer 5 or 6 inches directly about the heat flux sensor.

- Once you have obtained your plots and tables, return and work as a group to draw your final conclusions.

Examine the data that you collected. As you work towards answering the Challenge Question, answer the following questions:

1. What is the surface area for the heat flux in the case of:

Cooling in Water – A_s =

Heating in Air – A_s =

2. Estimate the heat flux from the rate of temperature change for cooling in water:

At Small Time

At Large Time

3. Estimate the heat flux from the rate of temperature change for heating in air:

At Small Time

At Large Time

4. Summarize the results and compare the values from the temperature measurements with the directly measured heat flux values.

Measurement	**dT/dt (°C/s)**	**q″ (W/m^2) from dT/dt**	**q″ (W/m^2) from heat flux gage**
Cooling at small time			
Cooling at large time			
Heating at small time			

Heating at large time			

Explain any differences. Is this what you expected?

5. Why are the heat flux values smaller at large time than small time?

6. Why is the rate of temperature change so much smaller for heating than cooling?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #3:
INTRODUCING TRANSIENT HEAT TRANSFER - CALORIMETERS

STEP 5: REFLECTION

Discuss and answer the following questions:

9. How does the temperature change with time?

10. How does heat flux change with time?

11. Can you predict the heat flux from the change in temperature? How?

12. What did you learn? What do you know now, that you didn't know before?

Workshop 4

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #4:
INTRODUCING TRANSIENT HEAT TRANSFER (SEMI-INFINITE MATERIALS)

THE CHALLENGE

Objective:

- Gain an understanding of the transient nature of heat transfer.
- Gain an understanding of thermal resistance.
- Gain an understanding of how to determine thermal properties of a material.
- Gain an understanding of the difference between heat, energy, and temperature.
- Gain an understanding of the difference between heat flux and temperature measurements.

Context and Challenge:

In the first workshop you were asked to compare the thermal characteristics of two materials. Your manager has now come back to you to measure the thermal conductivity of the new plastic product. It is also requested to determine the transient response of this material and a metal that will be used as part of the same system. To emphasize the distinction between the response between the metal and plastic, you decide to create a simple demonstration to make a lasting impression on your manager. You will have him put his hand on both materials at room temperature and feel the difference in thermal response and describe to him why it feels different.

Challenge Question:

Why does the metal feel different than the plastic?

Available Equipment:

In your laboratory, you have access to:

- The two material samples (density and specific heat are known):
  - Metal (steel)
    - $\rho = 7{,}800$ kg/m^3; C = 400 J/kg-K
  - Plastic
    - $\rho = 1{,}200$ kg/m^3; C = 1,200 J/kg-K
- A *temperature sensor* (a surface mount thermocouple),
- A *heat flux sensor*
- Both sensors are connected to a *data acquisition unit* (DAQ) that will record the results of the measurements taken from the two sensors.
- You can use *your hand* as a heat source to measure the difference in response of the two materials

Design an experiment wherein your team uses these tools to determine what is the insulation thermal conductivity and demonstrate why the materials feel different.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #3:
INTRODUCING TRANSIENT HEAT TRANSFER

STEP 1: GENERATE IDEAS

The goal of this phase is to establish a hypothesis for the expected behavior of the metal. As a team, discuss the following questions.

- What is the initial temperature of the two materials?

- How will the heat flux change as a function of time?

- How will the magnitude of the heat flux differ between the two materials?

- How will surface temperature change over time?

Thermal resistance is defined as:

$$R'' = \frac{T_{surface} - T_{initial}}{q''}$$

- How will thermal resistance change as a function of time? Sketch a plot of R'' as a function of time.

Next, frame your **<u>hypothesis</u>**: (write your answers in the spaces below)

- What will you use to find the thermal conductivity?

- How and why will the metal feel different from the plastic?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #3:
INTRODUCING TRANSIENT HEAT TRANSFER

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH & REVISE

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

Transient conduction is the interplay between the conduction of thermal energy through a material and the thermal capacitance of the material. Before the thermal energy can move farther into the material it must first increase the temperature of the material locally. Consequently, the process appears to be that of increasing temperature diffusing into the material. It is almost like a wave propagating from the surface. The distance that it moves is proportional to $\delta \sim \sqrt{\alpha t}$, where the thermal diffusivity of the material is $\alpha = k/\rho C$. Consequently, the heat flux (which is proportional to thermal conductivity over distance) will be inversely proportional to the penetration depth. The analysis for one-dimensional transfer into a semi-infinite (thick) material with a sudden change of the surface temperature gives

$$q'' = \frac{T_{surface} - T_{initial}}{\sqrt{\pi t}} \sqrt{k\rho C}$$

To appear semi-infinite the material just needs to be thick enough that the temperature on the back side does not change appreciably during the test.

Thermal Resistance

Thermal resistance is a measure of the resistance of a material to heat transfer. At steady state it is proportional to the thickness of the material divided by the thermal conductivity. For the transient case the effective thickness would change with time. The general definition for thermal resistance is

$$R'' = \frac{T_{surface} - T_{initial}}{q''}$$

This can be used with the data and with the analysis to compare measured versus theory.

In the first workshop (#1) you used transient heat flux and temperature measurements to qualitatively determine the thermal conductivity of two materials. Now you have the additional background to actually determine values of thermal conductivity.

STEP 3: RESEARCH AND REVISE

- Provide a sketch of the experiment that your team will conduct to answer the Challenge Question.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #3:
INTRODUCING TRANSIENT HEAT TRANSFER

STEP 4: TEST YOUR METTLE

Use the provided setup and sensors to conduct your experiments. Evaluate the materials' response to your hand by collecting heat flux and temperature data. Make sure to cover both the temperature and heat flux sensors equally to give the same thermal conditions for both sensors.

USING THE DAQ

- On the lab laptop, open the appropriate folder (Desktop/Workshops/Workshop_4)
- Select the appropriate Labview program ("Plastic" or "Metal")
- Press "Run" button (at top left) to collect 15 seconds of data.
- Sensor data is automatically saved to the "Input_Data" folder
- After you have obtained both data sets (plastic and metal) open Desktop/Workshops/Workshop_4/Output_Plots
- Select the Matlab m-file "wkshp_4.m"
- In Matlab click "Run" (the "Play" button)
- Enter your computer number, 1-5 (your number is written on the laptop)
- Print the resulting plots
    - Four plots will be printed: (i) material surface temperature and (ii) heat flux as a function of time for both material samples

EXPERIMENTAL SESSION

- Place the temperature sensor and the heat flux sensor near to each other on a material sample, with the second temperature sensor on the back side of the material.
- Collect temperature and heat flux data. Everyone in the group should collect a set of data.
    - Start the Labview program first, then after one or two seconds place the palm of your hand on your setup
- Use your hand as a heat source
    - Use your palm (not your fingertips)
    - Try to apply steady and uniform pressure over both sensors on the sample throughout the 15 second data collection period
- Everyone in the group should take a complete set of data. You can pick the best ones to use for your analysis.
- Once you have all obtained your plots, return to your table and work as a group to draw your final conclusions.

Examine the data that you collected. Identify the time at which you applied the thermal event (your hand). Use this as your time zero. Fill in the tables (one for plastic and one for metal). Plot your results for R″ versus time on the graph provided. Use the temperatures before the event to identify the proper initial temperature. Then calculate the values of thermal conductivity, k, using the measured R″ values, k =

Plastic

Time (s)	q″ (W/m^2)	$T_{surface} - T_{initial}$ (°C)	R″ (m^2-K/W)	k (W/m-K)

Metal

Time (s)	q″ (W/m^2)	$T_{surface} - T_{initial}$ (°C)	R″ (m^2-K/W)	k (W/m-K)

Time (s)

As you work towards answering the Challenge Question, answer the following questions:

- Does the material appear to be semi-infinite? Does the temperature on the back side of the material change?

- How does the thermal resistance change as a function of time?

- Why does the thermal resistance change with time?

- How does the value of thermal resistance vary between the two materials?

- Estimate the value of the thermal contact resistance between the sensors and the materials (R″ at zero time).

- What is the difference in heat flux between the two materials? Even though the initial temperature of the insulation and the aluminum are nearly the same, why does the metal feel much colder than the insulation?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #3:
INTRODUCING TRANSIENT HEAT TRANSFER

STEP 5: REFLECTION

Discuss and answer the following questions:

1. Is thermal resistance constant during a thermal event? Why?

2. Why were the thermal conductivity values for the metal unrealistic?

3. How does the heat flux experienced by your hand influence the temperature that you feel?

4. What did you learn? What do you know now, that you didn't know before?

Workshop 5

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #5:
INTRODUCING BOUNDARY LAYERS

THE CHALLENGE

Objectives:

- Gain an understanding of convection heat transfer coefficients.
- Gain an understanding of fluid thermal resistance.
- Gain an understanding of the factors affecting heat transfer coefficients.
- Gain an understanding of the difference between heat flux and temperature.

Context and Challenge:

You are a newly-hired engineer at MakerBot – a company that makes desktop-scale 3D Printers. Your team has discovered that the printed part quality significantly improves if there is a high value of heat transfer coefficient (100 W/m^2-K) over the heated flat build plate.

Your manager suggests using a fan to generate the necessary air flow, but has no idea how to orient the air flow over the plate. Should it flow parallel to the plate? Or should it flow perpendicular to the plate?

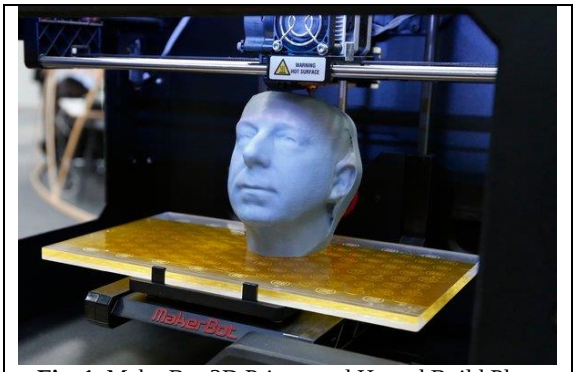


Fig. 1. MakerBot 3D Printer and Heated Build Plate

The team looks to you to determine the best fan orientation. Specifically, answer the following Challenge Question:

Challenge Question:

How should the fan be oriented to the plate in order to obtain the maximum uniform heat transfer coefficient?

Available Equipment:

Use the instrumentation supplied to investigate how the fan orientation affects convection over the plate. In your laboratory, you have access to:

- A thin plate, which is mounted on a thin electric heater.
- A fan.
- Two *temperature sensors*, (embedded thermocouples) mounted on the left and right sides of the plate.
- Two *heat flux sensors*
- A *thermocouple*, which is mounted at the exit of the fan to measure the air temperature
- Both sets of sensors are connected to a *data acquisition unit* (DAQ) that will record the results of the measurements taken from the two sensors.

Design an experiment wherein your team uses these tools to determine the optimum fan orientation.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #5:
INTRODUCING BOUNDARY LAYERS

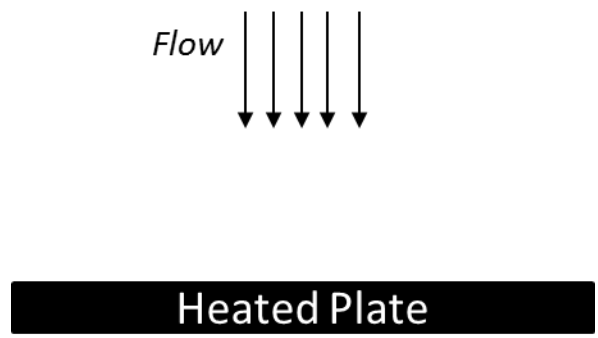
STEP 1: GENERATE IDEAS

The goal of this phase is to establish a hypothesis for the fan orientation.
As a team, discuss the following questions.

- What generally happens to the thermal boundary layer thickness as fluid flows along a plate? Provide a brief description and sketch a thermal boundary layer on a heated flat plate below.

- How is the heat transfer coefficient affected by the boundary layer thickness?

- For the case of perpendicular flow to the plate, provide a brief description and sketch a thermal boundary layer on a heated flat plate below.



Next, frame your **hypothesis**: (write your answers in the spaces below)

- What arrangement do you predict to give the largest heat transfer coefficient? Why?

- What arrangement do you predict to give the most uniform heat transfer coefficient? Why?

ME 3304: HEAT & MASS TRANSFER

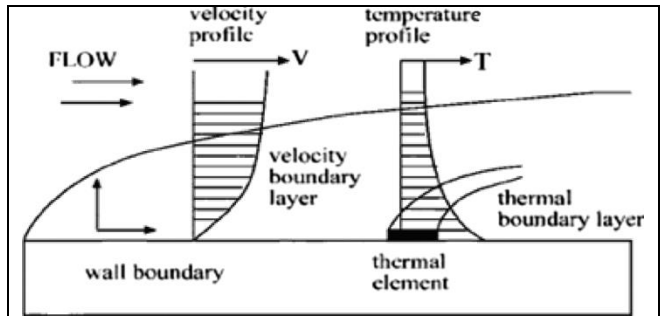
CHALLENGE-BASED WORKSHOP #5:
INTRODUCING BOUNDARY LAYERS

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH & REVISE

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

Boundary Layers



Boundary layers form in fluids next to solid surfaces as a function of the geometry and fluid motion. They represent the thermal resistance in the fluid between the surface and the free stream temperature of the fluid. The thermal boundary layer thickness is the distance from the body at which the temperature is 99% of the temperature found in the free stream.

Heat Transfer Coefficient

The heat transfer coefficient is defined as

$$h = \frac{q''}{T_{plate} - T_{air}}$$

The heat transfer coefficient represents the conduction of heat through the boundary layer next to the surface. Consequently, the heat transfer coefficient will be proportional to the thermal conductivity of the fluid and inversely proportional to the thermal boundary layer thickness.

Thermal Resistance

The thermal resistance of the boundary layer is the inverse of the heat transfer coefficient.

$$R'' = \frac{1}{h}$$

Consequently, the resistance increases as the boundary layer becomes larger for a given fluid thermal conductivity.

ME 3304: HEAT & MASS TRANSFER

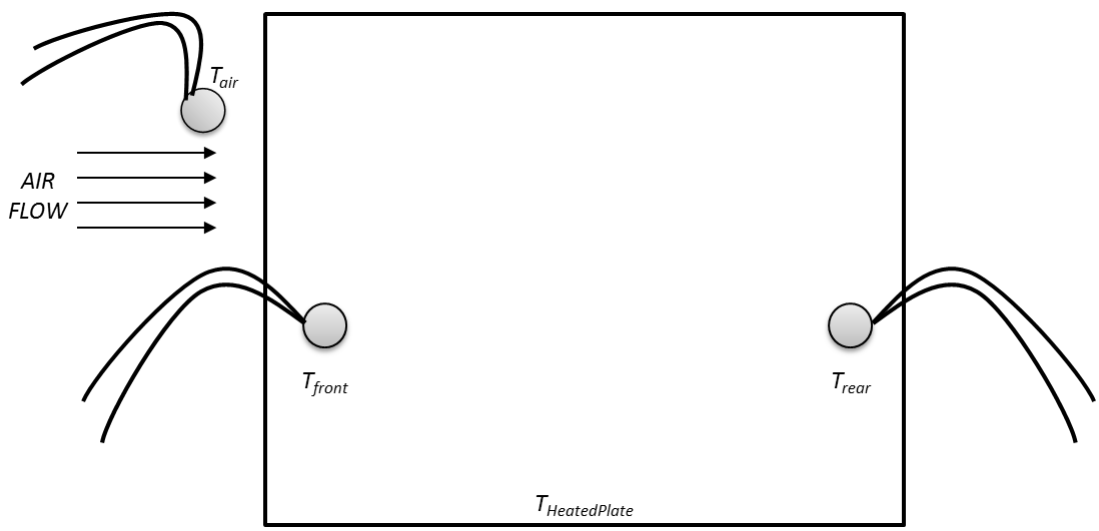
CHALLENGE-BASED WORKSHOP #5:
INTRODUCING BOUNDARY LAYERS

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH & REVISE

STEP 3: RESEARCH AND REVISE

- A preliminary sketch of the plate and temperature sensors is provided below. Complete the sketch to illustrate the setup that your team will use to answer the Challenge Question. (i.e., where will you place the heat flux sensors?)



How will your team determine the heat transfer coefficient?

- Provide the equation(s) you will use. State which variables you will be able to measure, and how they will be measured.

Update your hypothesis as needed given the information you gained in Step 2.

- What orientation do you predict to give the most uniform heat transfer coefficient?

- What orientation do you predict to give the largest heat transfer coefficient?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #5:
INTRODUCING BOUNDARY LAYERS

STEP 4: TEST YOUR METTLE

Use the provided sensors to conduct your experiments. **Your goal is to see how the fan orientation affects the heat transfer from surfaces.**

USING THE DAQ

- On the lab laptop, open the appropriate folder (Desktop/Workshops/Workshop_5)
- Select the Labview program ("Boundary_Layer")
- Press "Run" button (at top left) to collect 15 seconds of data.
- Sensor data is automatically saved to the "Input_Data" folder
- To analyze the data, open Desktop/Workshops/Workshop_5/Output_Plots
- Select the Matlab m-file "Wkshp_5.m"
- In Matlab click "Run" (the "Play" button)
- Enter your computer number, 1-5 (your number is written on the laptop)
- Enter if the data corresponds to is parallel or perpendicular air flow
- Print the resulting data (one sheet):

EXPERIMENTAL SESSION

- Place the heat flux sensors on the heated plate as your team decided
- The Labview program is set to take 15 seconds of data and then average the collected values over that time.
- First, orient the fan parallel to the plate.
- Start the fan and then start the data acquisition program.
    - The fan has a small button on the side that locks the fan to the "On" setting so that you don't have to hold the main button down the whole time.
- Run Matlab to print your results.
- Repeat the procedure for different fan orientations

Evaluate your Results:

- Air flow parallel to the plate with the gages at the front edge (to calculate h_{front}). Calculate:

T_{air} = q'' =

T_{plate} = hf_{ront} =

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #5:
INTRODUCING BOUNDARY LAYERS

STEP 4: TEST YOUR METTLE

- Air flow parallel to the plate with the gages at the back edge (to calculate h_{rear}). Calculate:

T_{air} = q'' =

T_{plate} = h_{back} =

- Air flow perpendicular to the plate with the gages (to calculate h_{right} & h_{left}). Calculate:

T_{air} = q''_{right} = q''_{left} =

T_{plate} = h_{right} =

h_{left} =

Examine the data that you collected and the heat transfer coefficient you calculated for each orientation. As you work towards answering the Challenge Question, answer the following questions:

- How does the position of the fan relative to the plate affect the measured value of the heat transfer coefficient?

- Which fan position has the largest value of heat transfer coefficient?

- Which fan position has the largest thermal resistance in the air?

- What does this indicate about the thickness of the thermal boundary layer in the air?

- Explain the relative values of the heat transfer coefficient you measured for the different fan orientations.

- Plot the profile of heat transfer coefficient as a function of distance along a plate for the different arrangements.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #5:
INTRODUCING BOUNDARY LAYERS

STEP 5: REFLECTION

Discuss and answer the following questions:

13. How does the heat transfer coefficient change over the distance of a plate? Why?

14. Which fan position should MakerBot use to get the highest convection? Why?

3. Which fan position should MakerBot use to get the most uniform convection? Why?

4. What did you learn? What do you know now, that you didn't know before?

Workshop 6

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
INTRODUCING INTERNAL FLOW

THE CHALLENGE

Objectives:

- Gain an understanding of convection heat transfer coefficients.
- Gain an understanding of fluid thermal resistance.
- Gain an understanding of the factors affecting heat transfer coefficients.
- Gain an understanding of the difference between heat flux and temperature.

Context and Challenge:

Your manager has an idea to cool a stream of gas using some aluminum square channels that are available. He wants you to size the system and evaluate its thermal performance. The channels are one-inch square outside dimensions, with a 1/16 inch wall thickness. Your challenge is to determine how long the channels need to be to cool the flow to below 30°C. The channel you have to test is four feet long.

Specifically, answer the following Challenge Question:

Challenge Question:

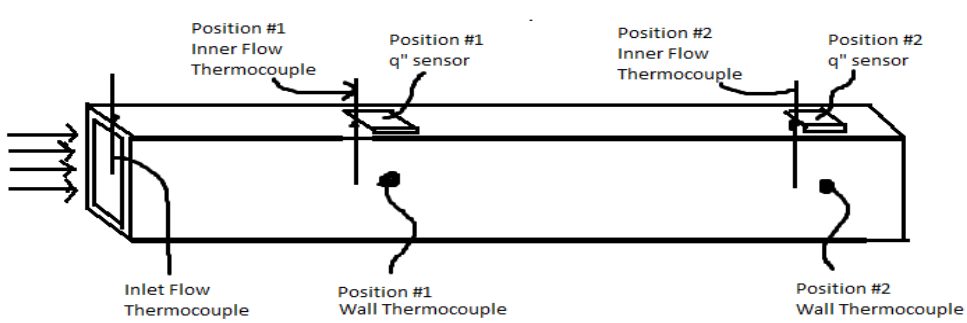
Based on your measurements, estimate the length of channel that will be required to satisfy the needed heat transfer.

Available Equipment:

Use the instrumentation supplied to investigate how convection affects the outlet temperature. In your laboratory, you have access to:

- A thin-walled channel, which has a *thermocouple* and *heat flux* sensor pair attached at two locations along the length of the channel.
- *Thermocouples* have been inserted into the flow at the inlet and also at two positions along the channel.
- A hair dryer supplies the heated flow with an air velocity that has been measured to be about 10 m/s.
- The four thermocouples and two heat flux sensors are connected to a *data acquisition unit* (DAQ) that will record the results of the measurements taken from the sensors.

Is this experiment sufficient for your team to determine the optimum channel length?



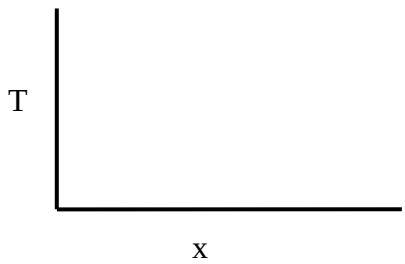
ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
INTRODUCING INTERNAL FLOW

STEP 1: GENERATE IDEAS

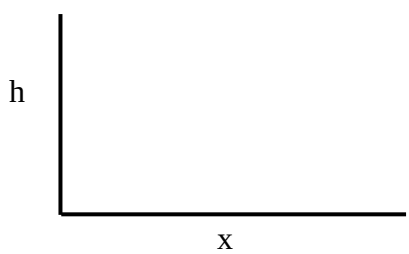
The goal of this phase is to establish a hypothesis for the channel operation.
As a team, discuss the following questions.

- What generally happens to the thermal energy as it is transported by the fluid flow in the channel? Provide a brief description and sketch the temperature of the flow as it goes down the channel in the x direction.



- How does the temperature of the channel wall change in the x-direction? Sketch it on the graph above.

- How does the heat transfer coefficient of the flow on the inside of the channel change in the x-direction? Sketch it on the graph below.



Next, frame your **hypothesis**: (write your answers in the spaces below)

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
INTRODUCING INTERNAL FLOW

STEP 1: GENERATE IDEAS

- Do you expect the flow in the channel to be laminar or turbulent? What is the resulting effect on the heat transfer coefficients?

- Do you expect there to be an entrance length in the channel like you observed with developing boundary layers on a flat plate? How would this be seen?

For flows inside of a conduit, the fluid temperature changes as the thermal energy is transferred into or out of the fluid. Moreover, the thickness of the fluid boundary layer is limited by the internal size of the structure. The flow can be either laminar or turbulent. The criterion is based on the Reynolds of the flow using the diameter of the tube as the length scale. The usual range for transition from laminar to turbulent flow is between Reynolds numbers of 2,000 and 10,000.

An energy balance on the flow can be used to relate the rate of enthalpy change of the fluid with the heat flux from the wall into the fluid

$$\dot{m}C_p\frac{dT}{dx} = q''P$$

where $\dot{m}$ is the mass flow rate of the fluid and P is the perimeter of the channel.

A popular correlation for the Nusselt number for turbulent flow in a tube is

$$Nu = 0.023\ Re^{.8}Pr^n$$

where n = 0.3 for cooling the flow. The property values for air at these temperatures are: k =0.028 W/m-K, C_p = 1,000 J/kg-K, ρ = 1.1 kg/m^3, ν = 1.8 x 10^{-5} m^2/s, Pr = 0.7.
There is also a definition for the hydraulic diameter for calculating the Reynolds number

$$D_h = \frac{4A_c}{P}$$

where A_c is the cross-sectional area of the channel and P is the wetted perimeter. The overall heat transfer coefficient is defined as

$$U_o = \frac{q''}{T_{flow} - T_{air}} = \left[\frac{1}{h_{outside}} + R''_{wall} + \frac{1}{h_{inside}}\left(\frac{A_o}{A_i}\right)\right]^{-1}$$

Note that the heat flux is measured on the outside of the channel. Consequently, because the heat transfer on the inside and outside of the channel must be the same, the area difference must be included

$$q = A_i q''_{inside} = A_o q''_{outside}$$

where A_i = L x Inside perimeter and A_o = L x Outside perimeter. The heat transfer coefficients will be in terms of the inside and outside fluid temperatures

$$h_{inside} = \frac{q''_{inside}}{T_{inside} - T_{wall}} \quad , \quad h_{outside} = \frac{q''_{outside}}{T_{wall} - T_{outside}}$$

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
INTRODUCING INTERNAL FLOW

STEP 3: RESEARCH & REVISE

On the table at the front of the room is a square aluminum channel with a combination of one thermocouple welded onto the outside channel wall, one thermocouple in the flow inside the channel and one heat flux gages mounted on the outside surface of the channel at two locations (positions 1 and 2 along the length of the channel). A hair dryer is used as the source of hot air flowing inside the channel. Use the large axial flow fan to circulate air on the outside of the channel. One thermocouple measures the entering air temperature and one thermocouple measures the outside air temperature.

How will your team determine the heat transfer coefficient?

- Evaluate the thermal resistance of the wall. The thermal conductivity of aluminum is k = 175 W/m-K. Is this resistance significant for heat transfer coefficients less than 100 W/m^2-K?

- Provide the equation(s) you will use to determine the heat transfer coefficient. State which variables you will be able to measure, and how they will be measured.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
INTRODUCING INTERNAL FLOW

STEP 4: TEST YOUR METTLE

Use the provided sensors to conduct your experiments. **Your goal is to observe the rate at which convection occurs as well as the changes the internal air temperature.**

- The Labview program is set to take 20 seconds of data and then average the collected values over that time.
- First, run with the external fan blowing across the channel.
- Start the hair dryer and direct the flow through the channel. Allow about 40 seconds to reach steady-state. Then start the data acquisition program.
- Run Matlab to print your results.

Evaluate your Results:

$T_{outside\ air}$ =

$T_{inlet\ air}$ =

Channel Position 1	Channel Position 2
q'' =	q'' =
T_{inside} =	T_{inside} =
T_{wall} =	T_{wall} =
h_{inside} =	h_{inside} =
$h_{outside}$ =	$h_{outside}$ =
$\frac{dT_{inside}}{dx}$ =	$\frac{dT_{inside}}{dx}$ =

Examine the data that you collected and the heat transfer coefficients you calculated. As you work towards answering the Challenge Question, answer the following questions:

- Is the heat transfer coefficient uniform on the inside of the channel? Why or why not?

- How do your values of heat transfer coefficient inside the channel match with those calculated from the correlation that was provided? Do you believe the values? Why?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
INTRODUCING INTERNAL FLOW

STEP 4: TEST YOUR METTLE

- Plot the profile of the temperatures as a function of distance along the channel.

- Estimate the length of channel required to reach an internal flow temperature of 30°C, L =

- Justify your value of L based on the plot and the values of $\frac{dT_{inside}}{dx}$ you calculated.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
INTRODUCING INTERNAL FLOW

STEP 5: REFLECTION

Discuss and answer the following questions:

1. What are the two reasons that the heat flux changes along the length of the channel?

2. Why does the value of $\frac{dT_{inside}}{dx}$ change along the length of the channel?

3. Why is the heat transfer coefficient different at positions 1 and 2 of the channel?

4. What general method could you use to determine the internal fluid temperature distribution as a function of the axial distance along the channel?

5. What did you learn? What do you know now, that you didn't know before?

Workshop 7

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #7:
CONTINUING INTERNAL FLOW

THE CHALLENGE

Objectives:

- Gain an understanding of convection heat transfer coefficients.
- Gain an understanding of fluid thermal resistance.
- Gain an understanding of the factors affecting heat transfer coefficients.
- Gain an understanding of the difference between heat flux and temperature.

Context and Challenge:

Last workshop your manager wanted to cool a stream of gas using aluminum square channels. You were to size the system based on heat flux and temperature measurements at two locations on the channel. Your challenge this week is to determine a better way to analyze and estimate the channel length needed to cool the flow to below 30°C. You have the same four foot long channel, but a number of additional thermocouples have been added to give more detail about the change in the flow temperature. Is there a model of the system that you can use for the entire temperature distribution in the channel to match with your measurements to extrapolate to the 30°C point?

Specifically, answer the following Challenge Question:

Challenge Question:

Based on your measurements and analysis, estimate the length of channel that will be required to satisfy the needed transfer.

Available Equipment:

Use the instrumentation supplied to investigate how convection affects the internal flow temperature. In your laboratory, you have access to:

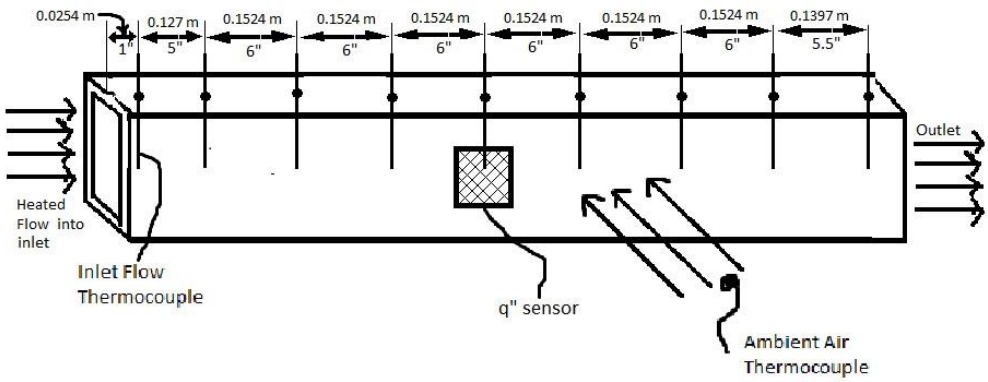
- A thin-walled channel, which has a thermocouple and heat flux sensor attached at one location along the length of the channel.
- Thermocouples have been inserted into the flow at 8 locations along the channel.
- A hair dryer supplies the heated flow with an air velocity that can be measured with a Pitot tube and manometer.
- A fan supplies room temperature air over the outside of the channel as the heat sink.
- The thermocouples and the heat flux sensor are connected to a *data acquisition unit* (DAQ) that will record the results of the measurements taken from the sensors.

Can you use the additional measurements and analysis provided this week to do a better estimate of the required channel length than last week?

ME 3304: HEAT & MASS TRANSFER

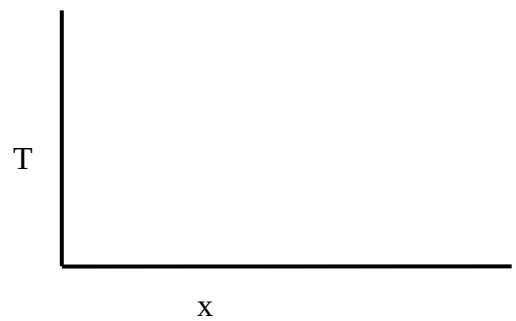
CHALLENGE-BASED WORKSHOP #7:
CONTINUING INTERNAL FLOW

STEP 1: GENERATE IDEAS

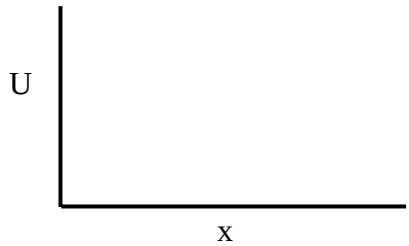


The goal of this phase is to establish a hypothesis for optimizing the channel operation. As a team, discuss the following questions.

- Sketch the expected temperature of the air on the <u>outside</u> of the channel and the temperature of the flow <u>inside</u> the channel in the x direction.



- How does the overall heat transfer coefficient U change in the x-direction? Sketch it on the graph below.



Next, frame your **<u>hypothesis</u>**: (write your answers in the spaces below)

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #7:
CONTINUING INTERNAL FLOW

STEP 1: GENERATE IDEAS

- If you can determine the overall heat transfer coefficient, can you predict the temperature profile throughout the channel length? How?

- Should the predictions match with the measured temperature values?

An energy balance on the flow can be used to relate the rate of enthalpy change of the fluid with the heat flux from the wall into the fluid

$$\dot{m}C_p\frac{dT}{dx} = q''P$$

where $\dot{m}$ is the mass flow rate of the fluid and P is the perimeter of the channel. In terms of a uniform temperature heat sink T_o, the temperature distribution is

$$\frac{T - T_o}{T_{inlet} - T_o} = exp\left(-\frac{UP}{\dot{m}C_p}x\right)$$

The average overall heat transfer coefficient is defined as

$$U_o = \frac{q''}{T_{flow} - T_{outside\ air}} = \left[\frac{1}{h_{outside}} + R''_{wall} + \frac{1}{h_{inside}}\left(\frac{A_o}{A_i}\right)\right]^{-1}$$

Last week you measured the heat transfer coefficients on the inside and outside of the channel. Often the more useful quantity is the overall heat transfer coefficient from the heat source to the heat sink. You can assume that the value you measure at the mid-point of the channel represents the average over the length of the tube. The property values for air at these temperatures are:
k =0.028 W/m-K
C_p = 1,000 J/kg-K
ρ = 1.1 kg/m^3
ν = 1.8 x 10^{-5} m^2/s
Pr = 0.7.

On the table at the front of the room is a square aluminum channel with a combination of eight thermocouples evenly spaced in the flow inside the channel and one heat flux gage mounted on the outside surface of the channel at center of the channel. A hair dryer is used as the source of hot air flowing inside the channel. Use the large axial flow fan to circulate air on the outside of the channel. One thermocouple measures the outside air temperature. A Pitot tube and manometer are available to measure the velocity of the internal flow at the exit of the channel. The Bernoulli equation is used to relate the measured pressure difference Δp to the velocity

$$\frac{1}{2}\rho V^2 = \Delta p$$

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #7:
CONTINUING INTERNAL FLOW

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH & REVISE

- How will your team determine the overall heat transfer coefficient from the measurements?

- Provide the equation(s) you will use to determine overall the heat transfer coefficient. State which variables you will be able to measure, and how they will be measured.

- How will your team determine the mass flow rate of the internal flow?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #7:
CONTINUING INTERNAL FLOW

STEP 4: TEST YOUR METTLE

Use the provided sensors to conduct your experiments. **Your goal is to observe the changes of the internal air temperature and show how to quantify it.**

- The Labview program is set to take 20 seconds of data and then average the collected values over that time.
- Start the hair dryer and direct the flow through the channel. Allow about 40 seconds to reach steady-state. While the temperatures are reaching steay state, measure the average flow velocity. Then start the data acquisition program for the temperatures and heat flux.
- Run Matlab to print your results and plot the inside temperature distribution.

Evaluate your measured results:

$T_{outside\ air}$ =

$T_{inlet\ air}$ =

Δp =

Velocity, V =

<u>Center Channel Position</u>
$q''_{outside}$ =
q''_{inside} =
T_{inside} =
$U_{outside}$ =
U_{inside} =

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #7:
CONTINUING INTERNAL FLOW

STEP 4: TEST YOUR METTLE

Examine the data that you collected and the heat transfer coefficients you calculated. As you work towards answering the Challenge Question, answer the following questions:

- Based on your measured overall heat transfer coefficient, calculate the predicted flow temperature as a function of distance x along the channel. Mark these values on the plot with the measured values. Include the distribution of the outside air temperature also.

- How do the calculated values compare with the measurements?
  What are the possible reasons for discrepancies?

- Based on your analysis, calculate the length of channel required to reach an internal flow temperature of 30°C. Show your algebraic and numeric answers.

  L =

  L =

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #7:
CONTINUING INTERNAL FLOW

STEP 5: REFLECTION

Discuss and answer the following questions:

1. What basic principle do you use to predict the change in flow temperature in the channel?

2. What assumption do you use about the overall heat transfer coefficient to predict the change in flow temperature along the channel?

3. How is the prediction method for the required channel length this week different than last week?

4. Is your calculation of the required channel length better than the last workshop? Why?

5. What did you learn? What do you know now, that you didn't know before?

Workshop 8

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #8:
MASS TRANSFER

THE CHALLENGE

Objectives:

- Gain an understanding of the mass transfer process.
- Gain an understanding of fluid mass transfer resistance.
- Gain an understanding of the relation between heat and mass transfer.

Context and Challenge:

Your manager has a cloth dying process that entails drying the cloth as the final step. The business is booming with a big new order and he wants to run the dryer at a higher speed by converting to a jet impingement dryer. The manufacturer has some rather outrageous claims and he wants you to check it out. As a first step, you are supplied with a single jet (with a fan) to test. You have available a heat flux sensor and thermocouples from previous workshops and a scales that can be used to measure the mass of water. Specifically, answer the following Challenge Question:

Challenge Question:

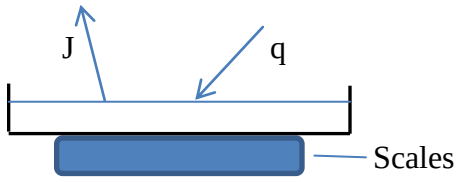
Is the air temperature and the transient effect important when determining the water evaporation rate for the jet impingement system?

Available Equipment:

Use the instrumentation supplied to investigate how convection affects the internal flow temperature. In your laboratory, you have access to:

- A small pan with a wet piece of cloth. A thermocouple has been inserted to monitor the water temperature.
- The pan sits on a scale to monitor its weight during evaporation.
- A plate with a heat flux sensor and thermocouple attached to the surface to measure the heat transfer coefficient from the jet.
- A hair dryer supplies the heated flow with a thermocouple to measure the temperature of the air supplied.
- A fan supplies room temperature air over the outside of the channel as the heat sink.
- The thermocouples and the heat flux sensor are connected to a *data acquisition unit* (DAQ) that will record the results of the measurements taken from the sensors.

Can you separate the mass transfer from the heat transfer? How are they connected?



ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #8:
MASS TRANSFER

STEP 1: GENERATE IDEAS

The goal of this phase is to establish a hypothesis for the evaporation process.
As a team, discuss the following questions.

- How much energy is required to evaporate water?

- What are the possible sources of the energy required for the evaporation?

- What is the effect of heating the air on the evaporation process?

Next, frame your **hypothesis**: (write your answers in the spaces below)

- If you measure the heat transfer coefficient, can you use that to help determine the source of energy for evaporation?

- If the thermal energy supplied is not sufficient for the mass transfer occurring, what will happen to the temperature of the water system?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #8:
MASS TRANSFER

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH & REVISE

The latent heat of vaporization describes the energy required for the phase change from liquid to vapor of water. At room temperature for water this has a value of approximately h_{fg} = 2440 kJ/kg. Consequently, the enthalpy of the evaporation is Jh_{fg}, where J represents the mass transfer rate in units of kg/s.

A transient energy balance can be used to relate the rate of energy change of the water in the pan with the heat flux into the water q'' and the mass flux J'' from the water

$$mC\frac{dT}{dt} = q''_{convection}A - J''h_{fg}A$$

with m the mass of the water in the pan and C = 4180 J/kg-K the specific heat. The three effects have to balance within the measurement error. At steady state the temperature of the water is no longer changing. This temperature is called the "wet bulb" temperature. It occurs when the convective heat transfer exactly matches the energy transfer required for the mass transfer. When the surface is above the wet bulb temperature the convection is lower and the mass transfer is higher, which causes the temperature to decrease. Below this temperature the opposite is true. The wet bulb temperature is a function of the humidity in the air and the temperature of the air. It increases as the humidity increases and the air temperature increases.

On the table at the front of the room is a pan of water on a scales with a thermocouple to measure the temperature. A hair dryer is used as the source of air flowing as a jet normal to the water surface. One thermocouple measures its air temperature. A plate with a heat flux sensor and surface thermocouple is also provided.

- Show how your team will determine the heat transfer coefficient. State which variables you will be able to measure, and how they will be measured.

- Show how your team will determine the mass transfer rate. Assume it is constant over the time of the measurement. What equations will you use?

- Show how your team will determine the rate of temperature change and the corresponding energy change. What equations will you use?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #8:
MASS TRANSFER

STEP 4: TEST YOUR METTLE

Use the provided sensors to conduct your experiments. **Your goal is to observe the rate at which evaporation occurs as well as the other two energy sources and sinks.**

- The first Labview program is set to take 20 seconds of data with a hair dryer and plate provided to determine the heat transfer coefficient provided by the hair dryer.
- First, turn on the hair dryer and let it warm up for 30 seconds. Put it normal to the plate, six inches away. Turn on the data acquisition to take data for 15 seconds. Select 'file: print window' at the top of the screen.
- Start the second Labview program, which runs for 120 seconds. Note the mass of the pan before and after applying the hair dryer normal to the pan, six inches away. Print window.
- Repeat the second test with the heater turned off (blue button). Hold button and blow air for 30 seconds to allow air to cool before testing.

Evaluate your measured results:

Plate Measurements

T_{air} = T_{plate} =

q''_{plate} = h =

Water Measurements (Hot Air) T_{air} =

Δm =

J =

a) Jh_{fg} =

$T_{initial}$ =

T_{final} =

$Aq''_{water\ conv}$ =

$Aq''_{water\ conv} - Jh_{fg}$ =

% Total Error in a) =

Measured transient $mC\frac{dT}{dt} =$

% Transient error in a) =

Water Measurements (Cool Air) T_{air} =

Δm =

J =

a) Jh_{fg} =

$T_{initial}$ =

T_{final} =

$Aq''_{water\ conv}$ =

$Aq''_{water\ conv} - Jh_{fg}$ =

% Total Error in a) =

Measured transient $mC\frac{dT}{dt} =$

% Transient error in a) =

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #8:
MASS TRANSFER

STEP 5: REFLECTION

Examine the data that you collected. As you work towards answering the Challenge Question, answer the following questions:

- What do the negative values for the cool air tests indicate about the energy transfer?

- How much lower is the heat flux in the cool case (%)?

- How much lower is the mass transfer in the cool case (%)?

- Why is there such a discrepancy in the change of heat flux vs. mass transfer between the hot and cool air cases?

- What should the value of $Aq''_{water\ conv} - Jh_{fg}$ be at steady-state (at the wet bulb temperature)?

- What is the biggest change in the test that should be instituted to achieve more accurate measurements of mass transfer?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #8:
MASS TRANSFER

STEP 5: REFLECTION

Discuss and answer the following questions:

1. Why is the wet bulb temperature always lower than the temperature of the air from the hair dryer?

2. Why does the temperature of the water change when the hair dryer is applied? Is there a situation in which it would not change?

3. Estimate how long you would have to wait to obtain a mass transfer measurement with less than 5% error due to transient effects. How could you check during the test?

4. Why is time of the test not a problem for the heat flux measurements?

5. What did you learn? What do you know now, that you didn't know before?

Workshop 9

ME 3304: HEAT & MASS TRANSFER

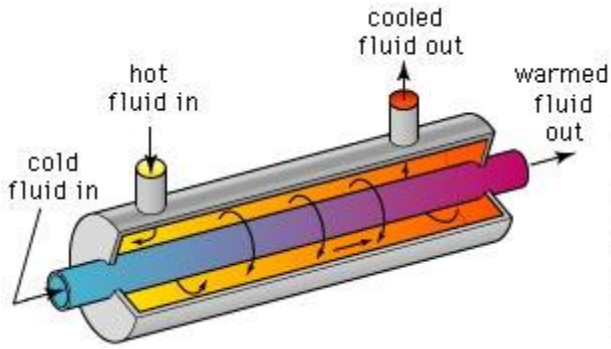
CHALLENGE-BASED WORKSHOP #9:
HEAT EXCHANGERS

THE CHALLENGE

Objectives:

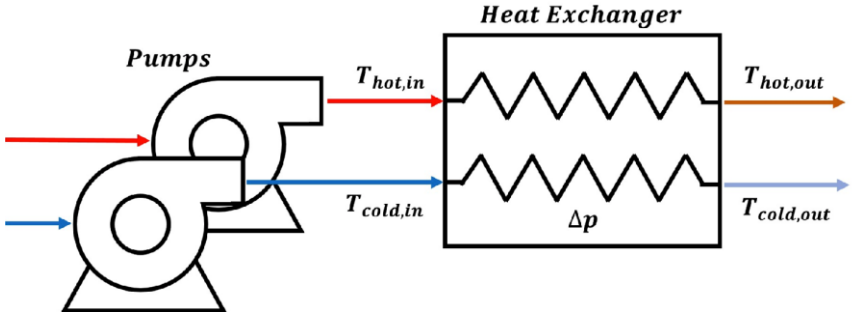
- Gain an understanding the of operation and design of heat exchangers
- Gain an understanding of the parameters used to quantify heat exchanger performance

Context and Challenge:



You are a design engineer for ACME Brewery. Beer sales have continued to increase, and your manager has asked you to redesign the heat exchanger to increase beer production. The aptly-named HT2CLD-2300 is a concentric tube heat exchanger, which is used for cooling in the beer brewing process. To help you in this task, a notebook in *Mathematica* has been created to allow for a dynamic simulation of the heat exchanger's performance. By adjusting the variable sliders, you can observe and record the effects from the temperature distribution plot and from the calculated values.

Your goal is to increase the production rate of beer by at least 50%, with a minimum increase of net power required into the system.



Challenge Question:

Can you provide the increased production with the current heat exchanger?

Available Equipment:

Your computers have been pre-loaded with Wolfram's CDF Player, which can run and play read-only Computable Document Format files saved by *Mathematica*, similarly to Adobe's PDF software. If you do not have access to a lab computer, you can download the free CDF Reader at the following link: https://www.wolfram.com/cdf-player/. Please download the CDF file and run it on your computer.

Design an efficient heat exchanger by optimizing a variety of parameters

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #9:
HEAT EXCHANGERS

STEP 1: GENERATE IDEAS

The goal of this section is to establish a hypothesis for which variables in a heat exchanger system are the most critical to the overall performance. Please do NOT open the *Mathematica CDF* file until instructed to do so.

As a team, discuss the following questions:

- What is the physical difference between a parallel-flow and counter-flow orientation of a heat exchanger? Sketch a diagram of the two different types and the flow directions of the hot and cold streams.

- Why can you simply not "max out" the efficiency of the heat exchanger? That is, what parameter can negatively affect the cost of operating the system, even if you design a very efficient heat exchanger? (*Hint: See Figure 2)*

- Do you think a larger mass flow rate would allow for more total heat transfer? Why or why not?

- What happens to the heat transfer coefficient when the mass flow rate is changed?

Next, frame your hypothesis:

- How do you propose to match the needed flow rates with the required heat transfer in the heat exchanger?

One of the most essential parameters to consider in the design and performance of any heat exchanger is the *overall heat transfer coefficient*, usually given as:

$$\frac{1}{UA} = \frac{1}{(hA)_{cold}} + R_{wall} + \frac{1}{(hA)_{hot}} \tag{1}$$

However, this expression applies for a "perfect," smooth heat transfer surface. In reality, fins are usually added to enhance heat transfer, and fluid impurities, rust buildup, or other chemical reactions can introduce another parameter called the *fouling factor*. For the purposes of this application, we can neglect the effects of fouling and use Equation (1). Furthermore, we can assume that there is negligible wall resistance, thus $R_{wall} = 0$.

In addition, we must consider the *total heat transfer* accomplished by the heat exchanger. We can calculate this using the overall heat transfer coefficient and the *log-mean temperature difference*, using an expression given by:

$$q = UA\,\Delta T_{lm} \tag{2}$$

where,

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{3}$$

$$\Delta T_1 = T_{hot,1} - T_{cold,1}$$
$$\Delta T_2 = T_{hot,2} - T_{cold,2} \tag{4}$$

where the 1 and 2 refer to the two ends of the heat exchanger. In addition, these temperature differences will use different values depending on whether we have a parallel or counter-flow heat exchanger.

Moreover, we can also express the total heat transfer, q, using values from either the hot or cold streams with:

$$q = (\dot{m}c_p)_{hot}(T_{hot,i} - T_{hot,o}) = C_{hot}(T_{hot,i} - T_{hot,o})$$
$$q = (\dot{m}c_p)_{cold}(T_{cold,i} - T_{cold,o}) = C_{cold}(T_{cold,i} - T_{cold,o}) \tag{5}$$

where C is the thermal capacity of the fluid. Keep in mind that, because the value of q from the hot stream must be equal to the value of q from the cold stream, any change in the variables in either expression must have a corresponding change in one of the values in the other expression. For example, a decrease in $c_{p,cold}$ would increase ΔT_{hot}, by either increasing $T_{hot,i}$ or decreasing $T_{hot,o}$.

Also, these expressions must also be equal to Equation (2), which leads to interesting design problems like what you face today. A "required" value of U can be found by setting one of these expressions in Equation (5) equal to Equation (2). However, changing the parameters of the heat exchanger will change the value of $U_{required}$, hence, you will have to continually balance the values of U_{actual} and $\dot{m}_c$.

Finally, you will have to compare how much more power is required to the pumps for each fluid stream. Remember from fluid dynamics that pump power, P, is given by:

$$P = \frac{\dot{m}}{\rho}\,\Delta p \tag{6}$$

where

$$\dot{m} = \rho V A_c, \;\; and\; \Delta p = f\,\frac{l}{D}\frac{\rho V^2}{2} \tag{7}$$

The friction factor f can be calculated with the simple Blasius correlation, since we will assume turbulent flow in a smooth pipe. Thus,

$$f = 0.316 Re^{-\frac{1}{4}} \tag{8}$$

Also recall that pump efficiency, η_p, is given by:

$$\eta_p = \frac{P_{out}}{P_{in}} = \frac{P}{P_{act}} \tag{9}$$

The pumps that are available for purchase from our local vendors are all listed at an efficiency of 65%. You will have to find the actual power required to the new pumps in order to provide the new mass flow rates for each stream.

Note that you will not have control over either of the temperatures for the beer stream, as the inlet and outlet temperatures are strictly part of the overall fermentation and beer brewing process. In addition, the inlet temperature of the coolant water will be set at 10**ºC**, as the chillers in the plant are only able to output at that temperature. The primary variables you have control of will be the **mass flow rate of the coolant water** $(\dot{m}_{cold})$ and the **overall heat transfer coefficient (U_{act}) of the heat exchanger.**

ME 3304: HEAT & MASS TRANSFER

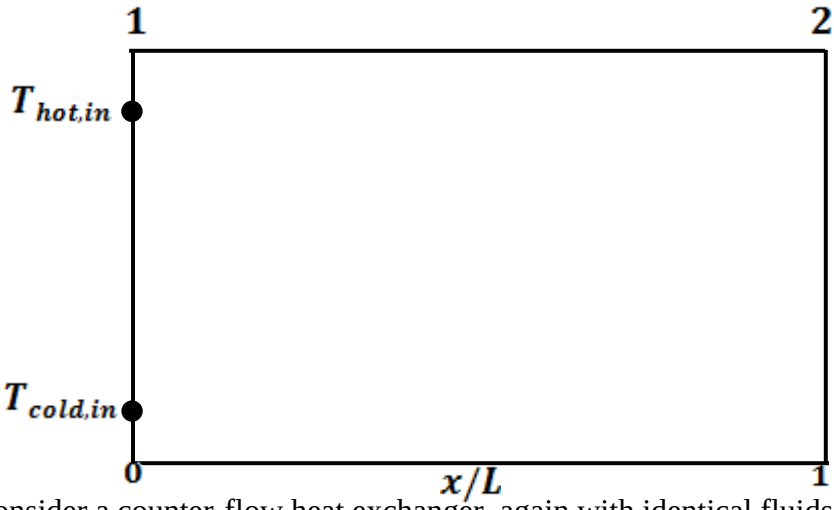
CHALLENGE-BASED WORKSHOP #9:
HEAT EXCHANGERS

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

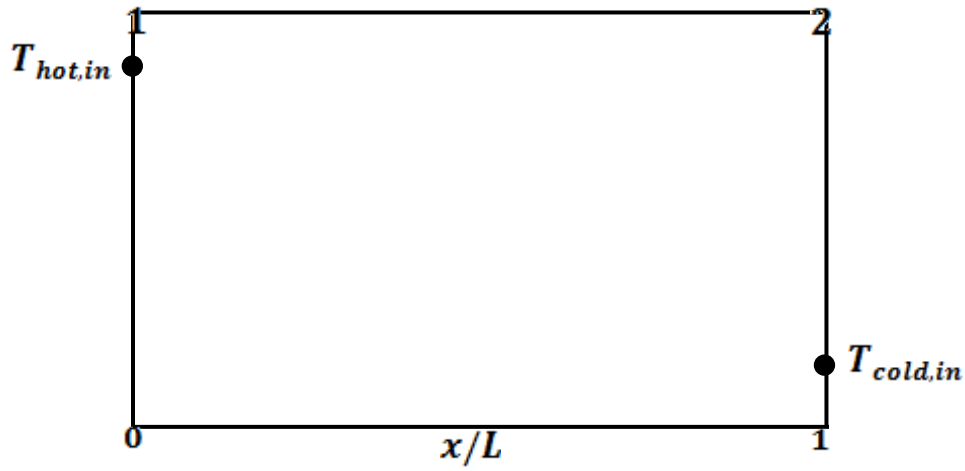
STEP 3: RESEARCH & REVISE

For this next section, you may open the Mathematica CDF file to aid you in answering the questions. However, try them on your own first before using the software to help you.

Now, consider a parallel-flow heat exchanger with two fluids at equal thermal capacities running through both the hot and cold streams. Sketch the expected behavior of the temperature distributions against the exposed surface area A/A_0 (dimensionless length).



Now, consider a counter-flow heat exchanger, again with identical fluids in both streams. What will the temperature distribution look like here?



ME 3304: HEAT & MASS TRANSFER

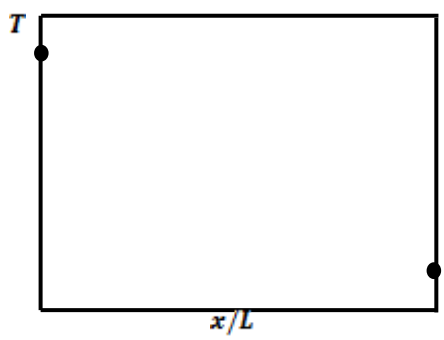
CHALLENGE-BASED WORKSHOP #9:
HEAT EXCHANGERS

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

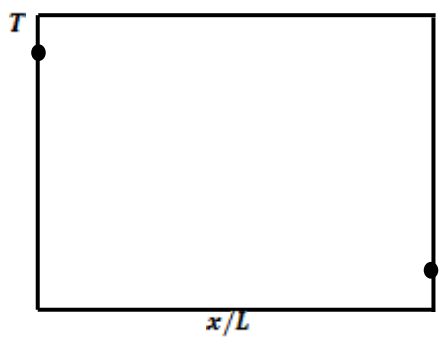
STEP 3: RESEARCH & REVISE

For a counter-flow heat exchanger, both fluids are water with $c_p = 4.2\frac{kJ}{kg \cdot K}$. Sketch the temperature plots for three different scenarios: $\dot{m}_{hot} = \dot{m}_{cold}$, $\dot{m}_{hot} >> \dot{m}_{cold}$, and $\dot{m}_{hot} << \dot{m}_{cold}$.

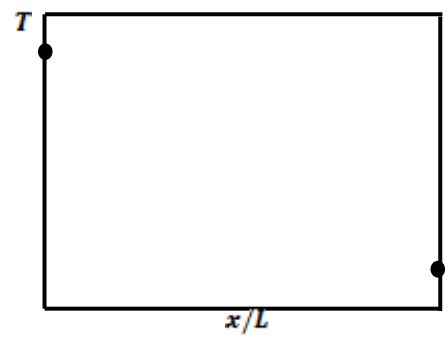
$\dot{m}_{hot} \gg \dot{m}_{cold}$



$\dot{m}_{hot} = \dot{m}_{cold}$

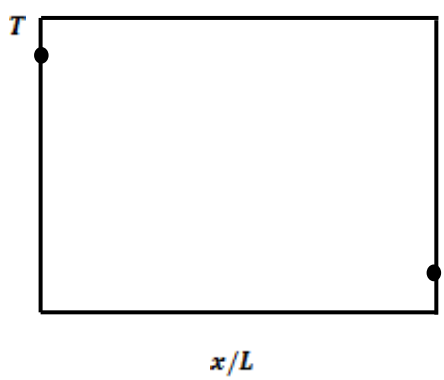


$\dot{m}_{hot} \ll \dot{m}_{cold}$

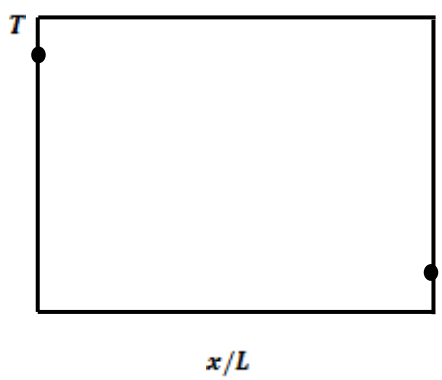


Again with a counter-flow heat exchanger, sketch the temperature distributions for three different levels of the overall heat transfer coefficient, U: zero, medium and high.

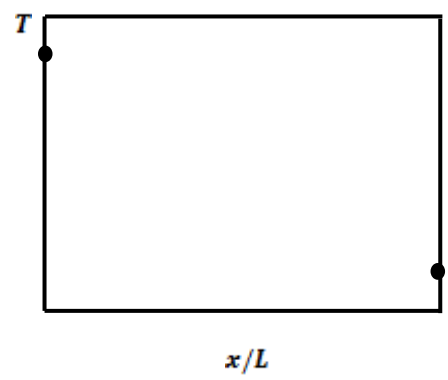
$U = 0$



$U > 0$



$U \gg 0$



ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #9:
HEAT EXCHANGERS

STEP 4: TEST YOUR METTLE

Use the provided Mathematica CDF file to conduct your experiments. **Your goal is determine a new set of parameters that will adequately cool the beer to 20ºC, while allowing for a 50% increase in the beer flow rate.**

- Clicking the small "+" symbol next to the sliders will open up a set of **fine controls**.
- The captions for temperature on the plot also have **built-in tooltips**: simply hover your mouse over the labels and the corresponding value of the temperature will be displayed.

The original values of the current heat exchanger system should be :

HX Dimensions	Beer Stream	Coolant Water Stream
$D_i = 0.02\ m$	$T_{h,in} = 80°C$	$T_{c,in} = 10°C$
$D_o = 0.04\ m$	$T_{h,out} = 20°C$	$T_{c,out} = 42°C$
$L = 14.9\ m\ ,\ \ A = 9.35\ m^2$	$\dot{m}_h = 1.00\ \frac{kg}{s}$	$\dot{m}_c = 1.85\ \frac{kg}{s}$
n = 10 tubes	$P_{h,in} = 1.77\ W$	$P_{c,in} = 1.4\ W$

$$q = 251\ kW$$

$$U_{act} = 1265\ \frac{W}{m^2\,°C}$$

List the values that you determined for one possible system setup:
In addition, print out a screenshot of your final system configuration to hand in.

Beer Stream	Coolant Water Stream
$T_{h,in} = 80°C$	$T_{c,in} = 10°C$
$T_{h,out} = 20°C$	$T_{c,out} =$
$\dot{m}_h = 1.50\frac{kg}{s}$	$\dot{m}_c =$
$P_{h,in} =$	$P_{c,in} =$

$$q =$$

$$U_{act} =$$

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #9:
HEAT EXCHANGERS

STEP 4: TEST YOUR METTLE

Examine your results and calculations. As you work towards answering the Challenge Question, answer the following questions:

- Were there other possible solutions to this design problem?

- What happens when U_{act} is not equal to U_{req}?

- Did the 50% increase in beer flow rate correspond to a 50% increase in total heat transfer required? Why or why not?

- If you had control of any other of the system parameters, which one(s) would you control and why?

- What happens when you try switching the configuration to a parallel-flow heat exchanger? What value is different and by how much? Why would you not want to use this in industry?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #9:
HEAT EXCHANGERS

STEP 5: REFLECTION

Discuss and answer the following questions:

1. Why does a counter-flow heat exchanger offer more performance than a parallel-flow type?

2. What parameters are interrelated? As in, which parameters are functions of other parameters?

3. What's wrong with just using room temperature (or hotter) cooling water and using a very high mass flow rate to achieve the same goals?

4. What did you learn? What do you know now, that you didn't know before?

Workshop 10

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #10:
RADIANT HEAT TRANSFER

THE CHALLENGE

Objective:

- Gain an understanding of radiant heat transfer
- Gain an understanding of radiation view factors
- Gain an understanding of the effects of surface emissivity and absorptivity

Context and Challenge:

You are to evaluate an infra-red heater for a new process to heat pieces of sheet metal. The first question is how the surface properties of the sheet metal affect the heat transfer. To answer this question one is painted with a high emissivity paint ($\varepsilon = 1$) while the second is left plain metallic.

Your goal is to determine the emissivity of the plain metal and evaluate its effect on the heat transfer from the infra-red heater. It is desired to provide a radiation heat flux to the metal sheet of 100 W/m^2. Can this be achieved and how?

Challenge Question:

Can you use the infra-red heater to process the metal sheets?

Available Equipment:

You are provided with a 12.7cm by 12.7cm heated plate that is painted black. There is also a piece of insulation with two 5.08cm by 5.08cm pieces of sheet metal. Thermocouples are attached to the surface of all of the plates.

Design a method to determine the emissivity of the metal plate

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #10:
RADIANT HEAT TRANSFER

STEP 1: GENERATE IDEAS

The goal of this section is to establish a hypothesis for how the infra-red heater operates and interacts with the metal sheets.

As a team, discuss the following questions:

- How does the surface conditions affect the thermal radiation that is emitted from a surface?

- How does the surface conditions affect the thermal radiation that is absorbed by a surface?

- Would the temperature rise of the metal sheet be affected by the surface absorptivity?

Next, frame your <u>hypothesis:</u>

- How do you propose to determine the metal absorptivity using the sheet that is painted black and the measured temperatures as a function of time?

The black body emissive power from a surface is given as

$$E_b = \sigma T^4 \tag{1}$$

where the Stefan-Boltzmann constant is $\sigma = 5.67 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m^2K^4}}$ and the temperature is in absolute Kelvin.

The heat flux that is actually emitted from a surface E is proportional to the emissivity of the surface

$$E = \varepsilon E_b = \varepsilon \sigma T^4 \tag{2}$$

The same is true for the radiation that is absorbed on a surface relative to the irradiation G (the radiation coming to a surface)

$$G_{absorbed} = \alpha G \tag{3}$$

where α represents the absorptivity of the surface. For gray and black surfaces Kirchoff's law applies

$$\alpha = \varepsilon \tag{4}$$

The absorptivity is equal to the emissivity! Consequently, the net radiation energy balance into a surface is simply what is absorbed minus what is emitted.

$$q''_{netin} = \alpha G - \varepsilon E_b = \varepsilon (G - E_b) \tag{5}$$

When two surfaces are involved, with one of them black, the resulting radiation exchange between them is

$$q''_{net1in} = \varepsilon_1 F_{12} (E_{b2} - E_{b1}) \tag{6}$$

where F_{12} is the view factor from surface 1 to surface 2. The view factor represents the fraction of energy leaving one surface that is intercepted by the other surface. Consequently, it is very dependent on the distance between the two surfaces and has values between zero and one.

As with the lumped capacitance model, an energy balance on the plate can be used to relate the rate of temperature change of the plate with the net heat transfer coming into the plate. This is often called a calorimeter. If the temperature rise is linear with time, it can be easily used to determine the net heat transfer

$$mC_p \frac{dT}{dt} = q''A \tag{7}$$

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #10:
RADIANT HEAT TRANSFER

STEP 4: TEST YOUR METTLE

You are provided with a heated plate that is 12.7 cm x 12.7 cm and painted black. It acts as the infra-red heater. Its temperature is maintained constant as measured by the attached thermocouple. Two thin aluminum sheets are mounted to a piece of insulation that can be placed over the heated plate. Each test sheet is 5.08 cm x 5.08 cm, weighs m = 5.5 grams and is made of aluminum with a specific heat of c_p = 910 J/kg-K. A thermocouple is welded onto each sheet. One sheet is painted black (ε = 1) and one is left natural. The thermocouples are all attached to the DAQ and recorded on the computer.

You can test two different positions of the sheets relative to the heated plate. The first is a distance of 10.5 cm away and the second is a distance of 7 cm away. **Make sure to put your hand at these two positions to feel the difference in heat flux from the plate.** At each distance use the measurements from the black sheet to find the view factor value, F_{12} . Assuming that the view factor is the same for the non-painted surface, determine its emissivity.

After the data run for each orientation, load the Matlab program in the Workshop 10 folder. The program will print a resulting plot and then delete your data.

<u>Test 1 (L = 10.5 cm)</u>

Black Sheet

dT/dt =

q_{1in}'' =

E_{b1} =

E_{b2} =

F_{12} =

Plain Sheet

dT/dt =

q_{1in}'' =

ε_1 =

<u>Test 2 (L = 7 cm)</u>

Black Sheet

dT/dt =

q_{1in}'' =

E_{b1} =

E_{b2} =

F_{12} =

Plain Sheet

dT/dt =

q_{1in}'' =

ε_1 =

Examine your results and calculations. As you work towards answering the Challenge Question, answer the following questions:

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #10:
RADIANT HEAT TRANSFER

STEP 4: TEST YOUR METTLE

- How do your results compare between Test 1 and Test 2?

- How can you achieve the required net heat flux of 100 W/m^2?

- Are the values of view factor reasonable?

- Are the values of emissivity reasonable?

- Do you believe how much difference the surface coating makes on the resulting heat flux?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #10:
RADIANT HEAT TRANSFER

STEP 5: REFLECTION

Discuss and answer the following questions:

1. What are the advantages and disadvantages of measuring the heat flux by this "calorimeter" method instead of the heat flux sensors used in previous workshops?

2. For the temperature range used were the values of heat flux from radiation more or less than those you previously measured from convection? Which method is more efficient at transferring heat over this temperature range?

3. Why did we neglect the radiation between the room and the metal sheets during these tests?

4. What did you learn? What do you know now, that you didn't know before?

Workshop 11

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #11:
GRAY BODY RADIANT HEAT TRANSFER

THE CHALLENGE

Objective:

- Gain an understanding of radiant heat transfer
- Gain an understanding of radiation view factors
- Gain an understanding of the effects of surface emissivity and absorptivity

Context and Challenge:

You are to evaluate an infra-red heater for a new process to heat pieces of sheet metal. Last week the question was how the surface properties of the sheet metal affect the heat transfer. This week is how the properties of the heater affect the heat transfer. Central to this investigation is how to calculate radiosities. Two heaters are now compared – one is painted with a high emissivity paint ($\varepsilon = 1$) while the second is left plain metallic.

Your goal is to determine the emissivities and radiosities of the different surfaces. It is still desired to provide a radiation heat flux to the metal sheet of 100 W/m^2. Can this still be achieved with both heaters?

Challenge Question:

Can you use either infra-red heater to process the metal sheets?

Available Equipment:

You are provided with two 12.7cm by 12.7cm heated plates. One is painted black, while the other is left plain. There is also a piece of insulation with two 5.08cm by 5.08cm pieces of sheet metal. Thermocouples are attached to the surface of all of the plates.

Design a method to determine the radiosities of the metal plate

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #11:
GRAY BODY RADIANT HEAT TRANSFER

STEP 1: GENERATE IDEAS

The goal of this section is to establish a hypothesis for how the infra-red heater operates and interacts with the metal sheets.

As a team, discuss the following questions:

- How does the surface conditions affect the thermal radiation that is emitted from a surface?

- How does the surface conditions affect the thermal radiation that is absorbed by a surface?

- Would the temperature rise of the metal sheet be affected by the surface emissivity of the heater? How?

Next, frame your <u>hypothesis:</u>

- How do you propose to determine the metal emissivity of the heater using one that is painted black and the other that is not?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #11:
GRAY BODY RADIANT HEAT TRANSFER

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH & REVISE

As described last week, when the heater is black, the resulting radiation exchange between the heater and plate is

$$\frac{q_{21}}{A_1} = \varepsilon_1 F_{12}(E_{b2} - E_{b1})$$

For the black plate the emissivity is one, while the emissivity is less than one for the gray metal plate. When the heater is gray, the radiation is not as simple and radiosities of the surfaces must be used. Radiosities can be determined from the following set of equations, depending on what is known. Note that standard notation is used, with q_1 being the net radiation <u>leaving</u> surface 1. Because it only exchanges radiation with the heater, $\mathbf{q_{21} = -q_1}$. The heater is surface 2 and the room is surface 3. You can assume that the room is black and remains at a temperature of 300K.

$$q_1 = \frac{E_{b1} - J_1}{\left(\frac{1-\varepsilon_1}{\varepsilon_1 A_1}\right)} \qquad q_2 = \frac{E_{b2} - J_2}{\left(\frac{1-\varepsilon_2}{\varepsilon_2 A_2}\right)}$$

$$J_1 = E_{b1} - \frac{(1-\varepsilon_1)}{\varepsilon_1}\frac{q_1}{A_1}$$

$$J_2 = \varepsilon_2 E_{b2} + (1-\varepsilon_2)(F_{21}J_1 + F_{23}E_{b3})$$

Note that when the emissivity of a surface is equal to one, the radiosity equals the black body emissive power. The heat transfer between two surfaces can be calculated by replacing the black body emissive powers with radiosities

$$q_{12} = A_1 F_{12}(J_1 - J_2)$$

As last week with the lumped capacitance model, an energy balance on the plate can be used to relate the rate of temperature change of the plate with the net heat transfer coming into the plate. This is often called a calorimeter. If the temperature rise is linear with time, it can be easily used to determine the net heat transfer

$$mC_p \frac{dT}{dt} = q''A \qquad (7)$$

You are provided with two heated plates that are 12.7 cm x 12.7 cm. One is painted black and one is left plain metal. They act as the infra-red heaters. Their temperatures are maintained constant as measured by the attached thermocouple. Two thin aluminum sheets are mounted to a piece of insulation that can be placed over the heated plate. Each test sheet is 5.08 cm x 5.08 cm, weighs m = 5.5 grams and is made of aluminum with a specific heat of c_p = 910 J/kg-K. A thermocouple is welded onto each sheet. One sheet is painted black (ε = 1) and one is left natural. The thermocouples are all attached to the DAQ and recorded on the computer.

Before you begin at a station, go to the front of the room. There is a red power supply heating two plates of the same size. One is painted black and the other is not. They should be at about the same temperature. Go up and carefully hold the back of your hand over one plate and then the other to feel the difference in radiation. **Be careful not to touch any of the plates. They are very hot.**

Go to your station and load the Labview Program "Radiosity – Black heater". Run the program for a few seconds to make sure the heater temperature is around 80 degC. If not, tell one of the TA's. Place the sheets on the blocks symmetric over the heater and let the program run for one minute. Load the Matlab program corresponding to the black heater. **Go back to a desk and start your calculations**. After each group has run through the black heaters, go back to your station and repeat the steps with the gray heater. There are two labview and two Matlab programs for this workshop.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #11:
GRAY BODY RADIANT HEAT TRANSFER

STEP 4: TEST YOUR METTLE

Use the measurements from the black heater and sheet to find the view factor value, F_{12} . Assuming that the view factor is the same for the non-painted surface, determine its emissivity, ε_1. Assume the metal plates have the same emissivity, $\boldsymbol{\varepsilon_2 = \varepsilon_1}$.

Test 1 **Black** Heater

Black Sheet

dT/dt =

q_{21}/A_1 =

E_{b1} =

E_{b2} =

F_{12} =

F_{21} =

F_{23} =

Metal Sheet

dT/dt =

q_{21}/A_1 =

ε_1 =

J_1 =

J_2 =

Test 2 **Metal** Heater

Black Sheet

dT/dt =

q_{21}/A_1 =

E_{b1} =

E_{b2} =

E_{b3} =

ε_2 =

J_2 =

q_2/A_2 =

Metal Sheet

dT/dt =

q_{21}/A_1 =

J_1 =

J_2 =

q_2/A_2 =

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #11:
GRAY BODY RADIANT HEAT TRANSFER

STEP 4: TEST YOUR METTLE

Examine your results and calculations. As you work towards answering the Challenge Question, answer the following questions:

- How do your results compare between Test 1 and Test 2?

- What options do you have to achieve the required net heat flux of 100 W/m^2?

- Are the values of radiosity reasonable? What would you expect relative to the black body emissive powers?

- Are the values of emissivities reasonable?

- Do you believe how much difference the surface coating makes on the resulting heat flux?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #11:
GRAY BODY RADIANT HEAT TRANSFER

STEP 5: REFLECTION

Discuss and answer the following questions:

1. Why is the radiosity of a gray surface different than the black body emissive power?

2. Are the radiosity values larger or smaller than the black body emissive powers? What determines this?

3. Why did we care about radiosity?

4. How would the values of q_2/A_2 vary from black to gray heaters?

5. What did you learn? What do you know now, that you didn't know before?

Appendix B: Second Semester Workshops
Videos can be found with file names: Cirenza_CF_T_2015_Appendix_B.zip
Additionally, they can be found at the following links:

Video 1: https://www.youtube.com/watch?v=0eNCni5Jzjs
"Introduction to Thermal Sensors," page 143

Video 2: https://www.youtube.com/watch?v=L55hUg-Fplc
"Workshop 1.1," page 145

Video 3: https://www.youtube.com/watch?v=hvOnRqyBfcc
"Workshop 1.2," page 145

Video 4: https://www.youtube.com/watch?v=vS0SZ-ONKoM
"Workshop 1.3," page 146

Video 5: https://www.youtube.com/watch?v=kC4kY4O-T4E
"Workshop 1.4," page 147

Video 6: https://www.youtube.com/watch?v=szFuwgYGrzw
"Workshop 2," page 155

Video 7: https://www.youtube.com/watch?v=mzj_RHOQ8YE
"Workshop 3," page 163

Video 8: https://www.youtube.com/watch?v=F4VGENsv9Qk
"Workshop 4," page 170

Video 9: https://www.youtube.com/watch?v=BPrEeEvJW1A
"Workshop 6," page 183

Workshop 1 (All Pages Filled Out Online Using Qualtrics)

ME 3304: HEAT & MASS TRANSFER
CHALLENGE BASED WORKSHOP #1:
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

THE CHALLENGE

Objective:

- Learn how temperature and heat flux sensors work
- Gain an understanding of the difference between heat, energy, and temperature.
- Gain an understanding of how to determine thermal properties of a material.
- Gain an understanding of the difference between heat flux and temperature measurements.

Challenge:

You are the lead engineer working for *NovaMaterials*, an engineering firm specializing in heat transfer research.

One of your clients recently shipped two material samples, one metal and one plastic, to your team for evaluation. These material samples are going to be used as a thermal barrier in a hydrogen fuel-cell automobile.

Your client knows very little about the materials, and has asked for your help in identifying their thermal properties. Specifically, answer the following challenge question:

Challenge Question:
Which material is more thermally conductive?

Available Equipment:

In your laboratory, you have access to

- a *temperature sensor* (a surface mount thermocouple),
- a *heat flux sensor*, and the material samples.
- In addition, your team is provided videos of the experiments being conducted and the resultant data set.

ME 3304: HEAT & MASS TRANSFER
CHALLENGE BASED WORKSHOP #1:
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 1: GENERATE IDEAS

Q1: What is the difference between temperature and heat flux?

Answer on Qualtrics

Q2: What is a typical thermocouple measurement?

25^oC
100W
77^oF
$100W/m^2$

Check all that apply, answer on Qualtrics

Q3: What is a typical heat flux measurement?

25W
25J
$25W/m^2$
25^oC

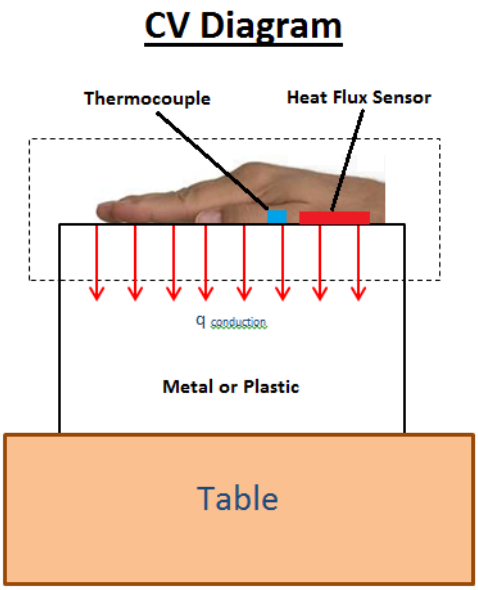
Answer on Qualtrics

ME 3304: HEAT & MASS TRANSFER
CHALLENGE BASED WORKSHOP #1:
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 1: GENERATE IDEAS

Q4: Frame your hypothesis:

Shown below is a diagram of the setup with a control volume around the modes of heat transfer taking place



Which material is more thermally conductive (plastic or metal)?

Answer on Qualtrics

Q5: If equivalent heat sources are placed on top of the metal and plastic plates, how will the temperature and heat flux measurements differ?

CONSULT WITH YOUR TA BEFORE MOVING ON TO THE NEXT STEP

ME 3304: HEAT & MASS TRANSFER
CHALLENGE BASED WORKSHOP #1:
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 2: GATHERING PERSPECTIVES AND RESOURCES & STEP 3: RESEARCH AND REVISE

The goal of this phase is to gain the background information necessary to further inform your hypothesis and your experimental plan.
As a team, review the background information below. Reflect on this information and adjust your hypothesis as necessary.

Overview of Heat Flux Sensors:
A heat flux sensor is a transducer that generates an electrical signal proportional to the total heat rate applied to the surface of the sensor. The measured heat rate is divided by the surface area of the sensor to determine the heat flux. Heat flux sensors generally have the shape of a flat plate and a sensitivity in the direction perpendicular to the sensor surface. Usually a number of thermocouples connected in series, called thermopiles, are used.

Overview of Surface Mount Thermocouple:
A thermocouple is a temperature-measuring device consisting of two dissimilar conductors that contact each other at one or more spots. It produces a voltage when the temperature of one of the spots differs from the reference temperature at other parts of the circuit.

To help you remember, here is a link to the intro video on thermocouples and heat flux sensors:

Video 1: "Introduction to Thermal Sensors"

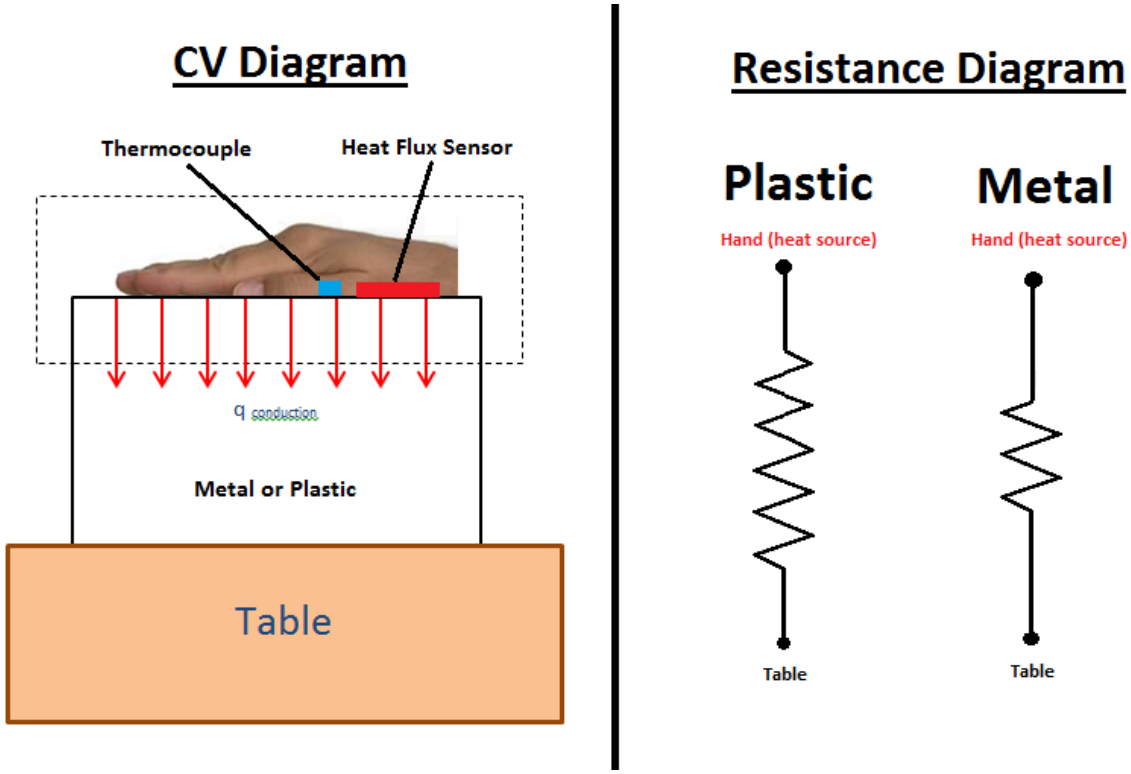
Review of Fourier's Law and Thermal Conductivity:
For heat conduction, the rate equation is known as Fourier's law. For a one-dimensional plane wall having a temperature distribution *T(x)*, the rate equation is expressed as:

$$q'' = -k(dT/dx)$$

- The heat flux, q" (W/m2) is the heat transfer rate in the x direction per unit area perpendicular to the direction of transfer. It is proportional to the temperature gradient, dT/dx, in this direction.
- The proportionality constant, k, is a transport property known as the thermal conductivity (W/mK). It is a material property.

ME 3304: HEAT & MASS TRANSFER
CHALLENGE BASED WORKSHOP #1:
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 2: GATHERING PERSPECTIVES AND RESOURCES & STEP 3: RESEARCH AND REVISE



Above diagram accompanies steps 2 and 3 on Qualtrics.

ME 3304: HEAT & MASS TRANSFER
CHALLENGE BASED WORKSHOP #1:
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 4: TEST YOUR METTLE

The goal of this phase is to answer the Challenge Question, and validate your hypothesis, via experimentation.

Your opbjects are to understand

1. the difference between heat flux and temperature,
2. how heat flux and tempearture are measured, and
3. the affects of materials on heatflux and temperature by interpreting the plots of the acquired data.

While you **WILL NOT** be taking data, you **WILL** perform the experiment while watching the data being taken on the video

Tips for the Sensors:

· Both the thermocouples and heat flux sensors are very fragile. Handle them carefully.

EXPERIMENTAL SESSION

Part 1
This first part of the video shows the setup of the experiment with the same plates and sensors that are placed in front of you. The video also shows the data acquisition instrument and LabVIEW software that will be used to record the data and plots in the video.

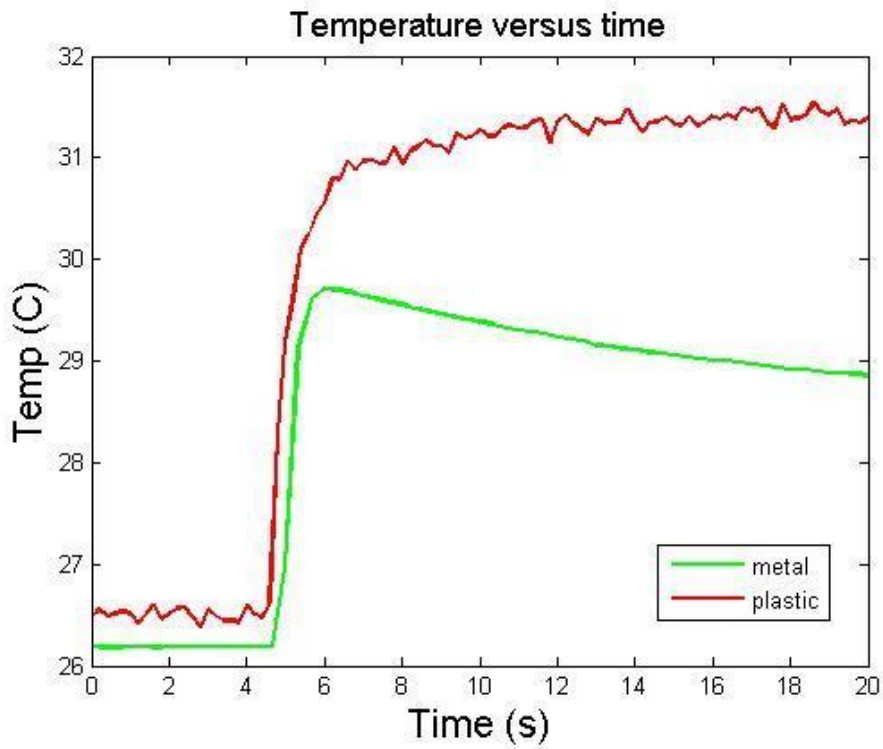
Video 2: "Workshop 1.1"
Part 1 is completed before moving onto part 2

Part 2
In this part of the video, hands are placed on a piece of aluminum and a piece of plastic. Notice how the hands are flush against the materials with the sensors sandwiched in between. Follow along and place your hands on the provided materials. **FEEL** the difference between the two different materials and **WATCH** the plots on the video record data in time .The plots in Part 1 show how the surface temperature changes with time. The surface temperature is recorded by the thermocouple on which you are placing your hand.

Video 3: "Workshop 1.2"

The following image is a MATLAB plot of variation of surface temperature with time for the two materials

STEP 4: TEST YOUR METTLE



(Plot provided with video)

Q6: Is the temperature increasing or decreasing over time for the two materials?

Answer on Qualtrics

Q7: How do the temperature measurements of the two materials compare to one another?

CONSULT WITH YOUR TA BEFORE MOVING ON TO THE NEXT STEP

Part 3

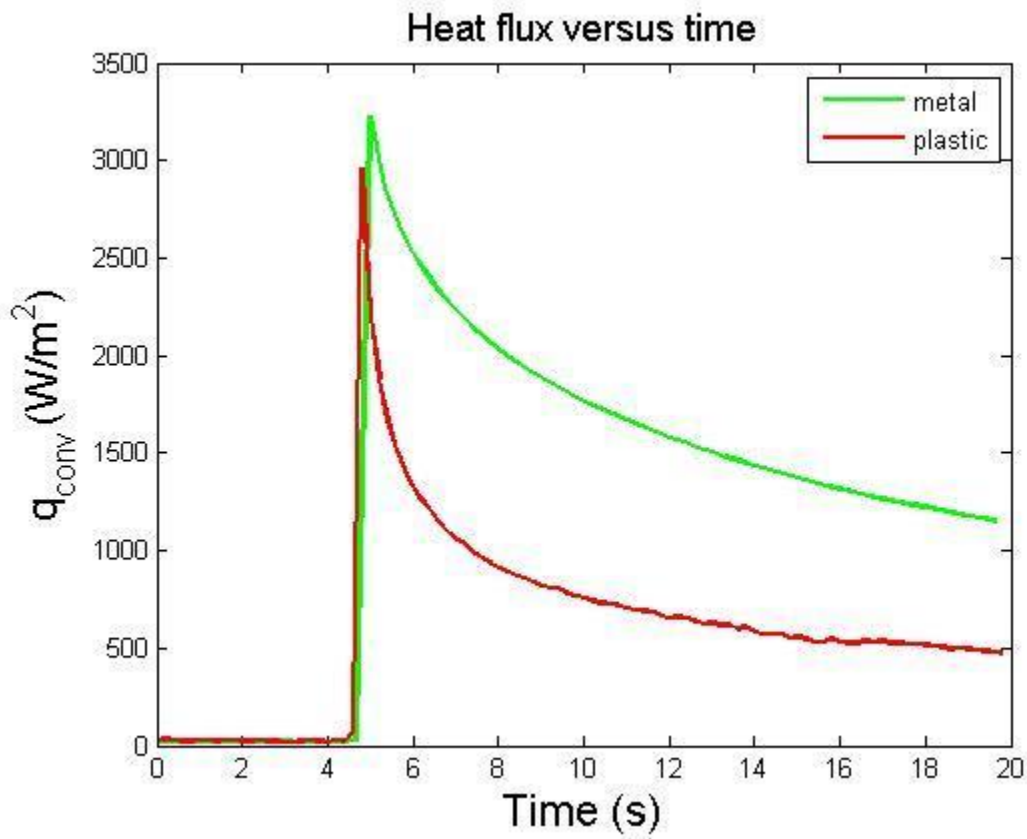
Repeat the steps in Part 2. Note that the plots displayed are now of heat flux instead of temperature.

Video 4: "Workshop 1.3"

The following image is a MATLAB plot of variation of heat flux with time for the two materials.

ME 3304: HEAT & MASS TRANSFER
CHALLENGE BASED WORKSHOP #1:
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 4: TEST YOUR METTLE



(Plot provided with video)

Q8: Is the heat flux increasing or decreasing over time for the two materials?

Answer on Qualtrics

Q9: How do the heat flux measurements of the two materials compare to one another?

CONSULT WITH YOUR TA BEFORE MOVING ON TO THE NEXT STEP

Part 4

This last video shows the experiment from the perspective of an thermal camera. While watching the video, observe the colors on the temperature scale and think about how the previous plots of temperature and heat flux explain the recording from the camera.

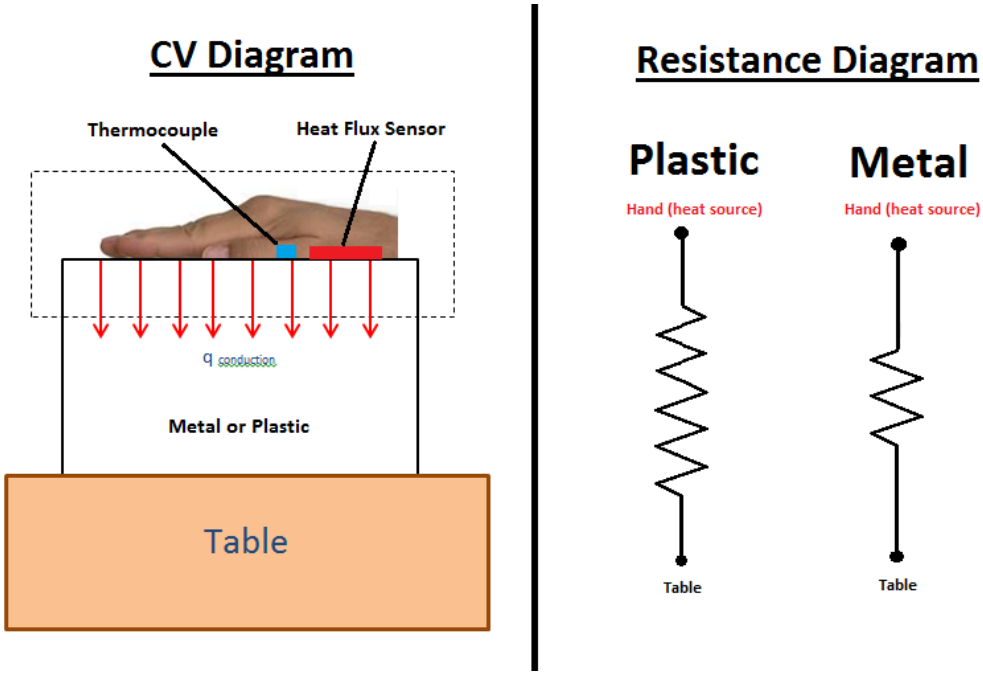
Video 5: "Workshop 1.4"

Q10: Which material appears to have a higher surface temperature as seen by the thermal camera? Does this agree with the previously acquired data?

CONSULT WITH YOUR TA BEFORE MOVING ON TO THE NEXT STEP

ME 3304: HEAT & MASS TRANSFER
CHALLENGE BASED WORKSHOP #1:
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 4: TEST YOUR METTLE



(Diagrams provided again)

Notice that the plastic plate has a higher thermal resistance than the metal plate.

As you work towards answering the Challenge Question, answer the following questions:

Q11: Are the tests that you are conducting transient or steady-state? How do you know?

Answer on Qualtrics

Q12: Which material has a larger temperature change?

Answer on Qualtrics

Q13: Which material has a larger heat flux?

Answer on Qualtrics

Q14: How is the thermal conductivity related to these different responses?

CONSULT WITH YOUR TA BEFORE MOVING ON TO THE NEXT STEP

ME 3304: HEAT & MASS TRANSFER
CHALLENGE BASED WORKSHOP #1:
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

STEP 5: REFLECTION

The goal of this phase is to reflect on the data acquired in your experimentation and to answer the Challenge Question.

Discuss and answer the following questions

Q15: What different information is provided by the heat flux versus the temperature measurements?

Answer on Qualtrics

Q16: Did the experimental results verify with your hypothesis from Step 1? Why or why not?

Answer on Qualtrics

Q17: What did you learn from this exercise? What do you know now, that you didn't know before? *(This is an important question! Take time to reflect!)*

Answer on Qualtrics

Q18: Why does the metal feel colder than the plastic?

CONSULT WITH TA BEFORE FINISHING

Workshop 2 (Information and videos on Qualtrics, questions answered on separate sheets)

ME 3304: HEAT & MASS TRANSFER
CHALLENGE-BASED WORKSHOP #2:
EXTENDED SURFACES (FINS)

THE CHALLENGE

Objective:

- Learn how fins affect heat transfer.
- Learn the relation between conduction and convection heat transfer in a fin.
- Learn how the convection coefficient affects fin heat transfer .
- Learn how the convection coefficient affects fin efficiency.

Challenge:
You are the lead thermal engineer working for *PowerElectronics*, an engineering firm specializing in the design and manufacture of high-power, portable energy devices.

Your colleague, a mechanical designer, has asked for your help in specifying extended surfaces (fins) for a new device to help with thermal management issues in the design.

Specifically, you are asked to determine the convection heat transfer coefficient for the designed fin at three different air speeds. One with no air blowing over it, one with a fan set to a low speed setting, and one with a fan set to a high speed setting.

Challenge Questions:

• How does the convection coefficient and overall heat transfer change for the specified fin at three different air speeds?

• What is the corresponding change in fin efficiency?

Available Equipment:

Your experimental setup is composed of:

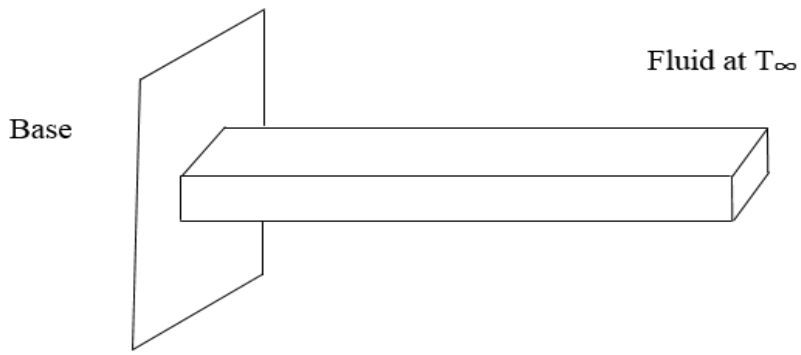
- A straight *fin* of uniform cross section has been attached to the lab table. The fin is 23.5 cm long, 3.7 cm wide, and 0.48 cm thick.
- A *heater* is located at the base of the fin to act as a heat source.
- Five (5) *temperature sensors* have been embedded into the fin along its length. One at the heater (x=0), and four along evenly spaced along its length (5 cm, 10 cm, 15 cm, and 20 cm).
- An additional *temperature sensor* is present to capture the temperature of the surrounding air. The surrounding air acts as the heat sink.

Use these tools to determine the convection coefficient and temperature distribution at three air speeds.

ME 3304: HEAT & MASS TRANSFER CHALLENGE-BASED WORKSHOP #2:EXTENDED SURFACES(FINS)
STEP 1:GENERATE IDEAS

The goal of this phase is to establish your experimental plan to answer the Challenge Questions. As a team, discuss the following questions; use the answers to help motivate your strategy.

Sketch and label where conduction and convection takes place on the fin schematic provided. Clearly label the heat source and the heat sink on the sketch.



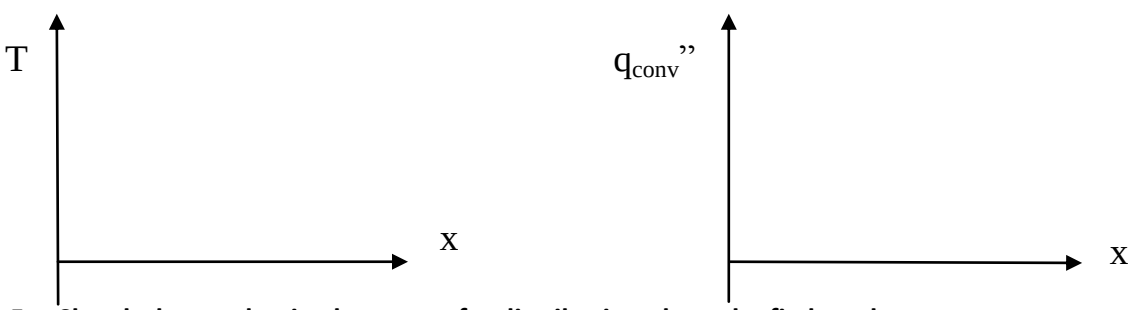
Next, frame your **hypothesis**: (write your answers in the spaces below).

1. **How will the convection coefficient change as the air speed is increased?**

2. **How does an increase in convection coefficient affect overall fin heat transfer?**

3. **How does an increase in convection coefficient affect the fin efficiency?**

4. **Sketch the temperature and convective heat flux distribution along the fin length.**



5. **Sketch the conductive heat transfer distribution along the fin length.**

(This sheet filled out offline)

ME 3304: HEAT & MASS TRANSFER
CHALLENGE-BASED WORKSHOP #2:
EXTENDED SURFACES(FINS)

STEP 2:GATHERING PERSPECTIVES AND RESOURCES
STEP 3: RESEARCH AND REVISE

The goal of this phase is to gain the background information necessary to further inform your hypothesis and your experimental plan.

As a team, review the background information below.

Review of Newton's Law of Cooling and the Convection Coefficient

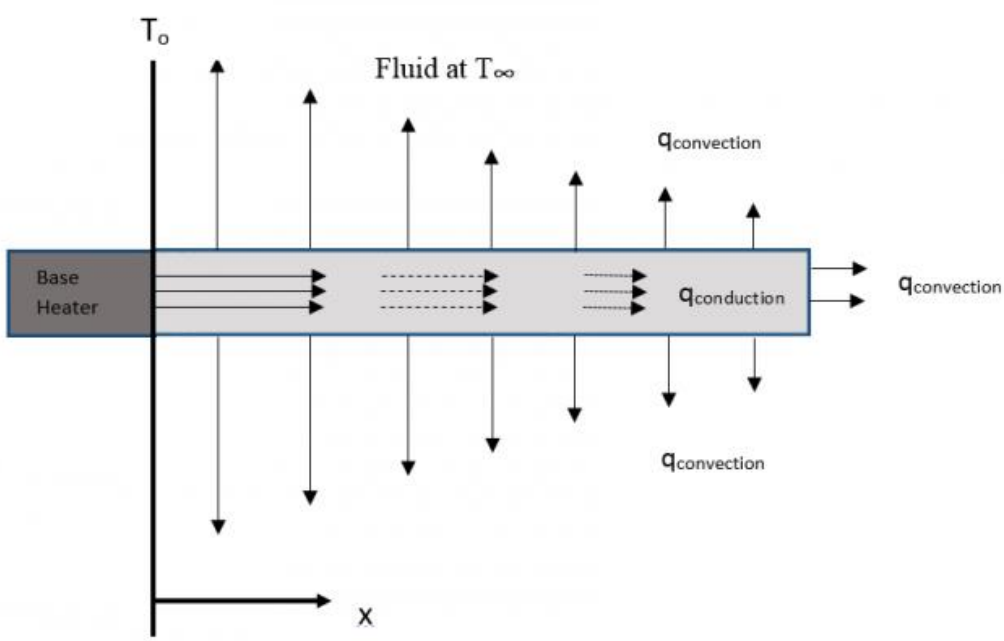
For heat convection, the rate equation is known as Newton's Law of Cooling. The rate equation is expressed as:

$q'' = h(T_S - T_\infty)$

The convective heat flux, q'' (W/m^2) is proportional to the difference between the surface and fluid temperatures, T_s and T_∞,at each location along the length of the fin.

The proportionality constant, h, is termed the convection heat transfer coefficient (W/m^2-K). It depends on conditions in the boundary layer, which are influenced by surface geometry, the nature of the fluid motion, and an assortment of fluid thermodynamic and transport properties.

The following figure illustrates the heat transfer in a fin



Evaluating Fin Performance

The ultimate goal of a fin is the transfer of thermal energy (q_{fin}) between a surface and a fluid.

The amount of surface area added by the fin is therefore an important aspect of the problem in determining q_{fin}. Note that the temperature distribution along the length of the fin (x-direction) is not uniform.

Another important measure of fin performance is the fin efficiency. The measurement of fin efficiency relates how efficiently the surface area of the fin is used to transfer thermal energy between the fin and the surroundings.

Fin efficiency, η, is defined as the ratio of the actual fin heat transfer to the ideal (maximum) fin heat transfer:

$$\eta = q_{fin}/q_{max}$$

Maximum fin heat transfer (qmax) would occur if the entire fin was uniform at the base temperature and is given by the expression

$$q_{max} = hA_s(T_o - T_\infty)$$

where T_o is the temperature of the fin base and A_s is the surface area of the fin.

ME 3304: HEAT & MASS TRANSFER CHALLENGE-BASED WORKSHOP #2: EXTENDED SURFACES(FINS)
STEP 4:TEST YOUR METTLE

Your goal is to understand the heat transfer in fins, how it varies with the length of the fin and how the air speed affects it.

EXPERIMENTAL SESSION:

Placed on the table is a fin which is heated at the base. Use your hand to **FEEL** the fin temperature at various locations to get an idea of where the most convection heat transfer is taking place.

Q6: Does the fin feel like its in steady state? How can you tell?

Answer on Qualtrics

The following video shows you the experimental setup and procedure required for temperature and heat flux measurements of the fin.The locations of the six thermocouples are fixed.

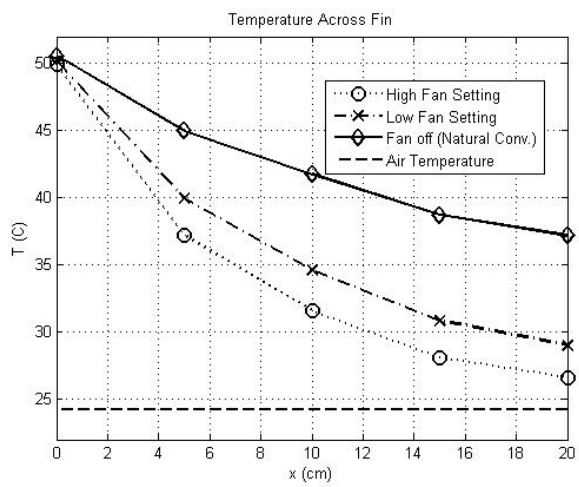
Video 6: "Workshop 2"

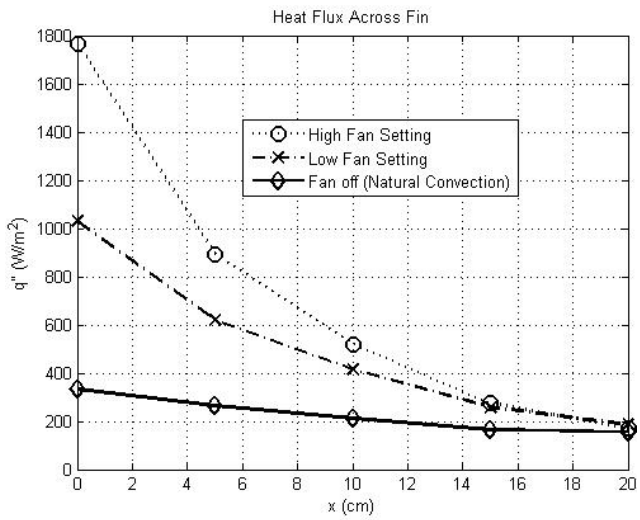
Follow along and answer the questions on the provided worksheet. Use the above video to assist you. Do not click finish button until you are finished and no longer need to use the video.

ME 3304: HEAT & MASS TRANSFER
CHALLENGE-BASED WORKSHOP #2:
EXTENDED SURFACES(FINS)

STEP 4:TEST YOUR METTLE

The following graphs show the temperature and heat flux distributions along the length of the fin for the three different air speeds. <u>ESTIMATE</u> the fin efficiencies for the three air speeds by looking at both graphs (you should get the same results from the two graphs).





η_f	no fan	high fan	low fan

η_f	no fan	high fan	low fan

The following Table shows a sample of the data from the above plots. Calculate values of the heat transfer coefficient (h) for the three different air speeds at the three different positions.

Air Temperature: T_{air} = 24.2 ^oC									
	x=0 cm			x=10 cm			x=20 cm		
	q" $(\frac{W}{m^2})$	T_f (^oC)	h $(\frac{W}{m^2K})$	q" $(\frac{W}{m^2})$	T_f (^oC)	h $(\frac{W}{m^2K})$	q" $(\frac{W}{m^2})$	T_f (^oC)	h $(\frac{W}{m^2K})$
Fan off	**332**	**50.6**		**212**	**41.8**		**156**	**37.2**	
Low fan	**1030**	**50.2**		**414**	**34.7**		**186**	**29.0**	
High fan	**1767**	**49.9**		**519**	**31.6**		**170**	**26.6**	

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ME 3304: HEAT & MASS TRANSFER CHALLENGE-BASED WORKSHOP #2: EXTENDED SURFACES(FINS)
STEP 4:TEST YOUR METTLE

Now that you have estimated the fin efficiencies and calculated the values for heat transfer coefficients (h), given the total fin surface area A_s= 200cm^2 and ΔT= 50-24=26 ^oC, you can now calculate the heat loss (q) and maximum heat loss (q_{max}) for each of the fan settings.

	No Fan	Low Fan	High Fan
η_f (estimated in step 4)			
h (calculated in step 4)			
q_{max}			
q			

How does the increase in convection coefficient affect the heat transfer from the fin?

How does the increase in convection coefficient affect the fin efficiency?

How does the change in air speed affect the temperature distribution and overall heat transfer in the fin?

Are there any differences in your preliminary temperature and heat flux distribution sketches and those obtained from the experiment? Why or why not?

Did your results agree with your hypothesis from Step 1? Why or why not?

What did you learn? What do you know now, that you didn't know before?

Workshop 3 (Information and videos on Qualtrics, questions answered on separate sheet)

ME 3304: HEAT & MASS TRANSFER
Challenge-based workshop #3:
Introducing Boundary Layers

THE CHALLENGE

Objectives:

- Gain an understanding of convection heat transfer coefficients.
- Gain an understanding of fluid thermal resistance.
- Gain an understanding of the factors affecting heat transfer coefficients.
- Gain an understanding of the difference between heat flux and temperature.

Context and Challenge:

You are a hardware engineer working for Intel and are trying to find the best method to cool a bank of transistors in a circuit. You have two choices. One involves placing the bank on a very thin sheet of aluminum and using a fan to blow air across the bank in one direction. The other involves placing the bank on a thick sheet of aluminum and blowing air across it. Which method and plate thickness will give the most uniform heat transfer and temperature to better cool the bed of transistors?

Challenge Question:
What plate thickness yields the most uniform heat flux, surface temperature, and heat transfer coefficient? How do the distributions of those three relate to the average values?

Available Equipment:

Use the video software and provided materials to investigate how plate thickness affects convection over the plate. In your laboratory, you have access to:

- A thin plate and a thick plate which are mounted on an electric heater.
- A fan.

The video software uses thermocouples, heat flux sensors, and a thermal camera to attain measurements and Labview and Matlab software to show results and plots.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #5:
INTRODUCING BOUNDARY LAYERS

STEP 1: GENERATE IDEAS

The goal of this phase is to establish a hypothesis to answer the challenge question.
As a team, discuss the following questions.

- What generally happens to the thermal boundary layer thickness as fluid flows along a plate? Provide a brief description and sketch a thermal boundary layer on a heated flat plate below.

- Hold the fan parallel to the plates on the heater and turn it on so that the air blows across both the plates in one direction. Feel the plates on the side close to and away from the fan.

- Having felt the plates, think about how temperature and heat flux are affected by the boundary layer for both the thick and thin plates. Discuss this with your partner and sketch two plots (one for the thick plate and one for the thin plate) below for temperature, heat flux, and h across the plates.

- How is the heat transfer coefficient affected by the boundary layer thickness?

Next, frame your **hypothesis**: (write your answers in the spaces below)

- Which plate do you predict to give the larger average heat transfer coefficient? Why?

- Which plate do you predict to give the larger amount of heat transfer? Why?

This sheet filled out offline

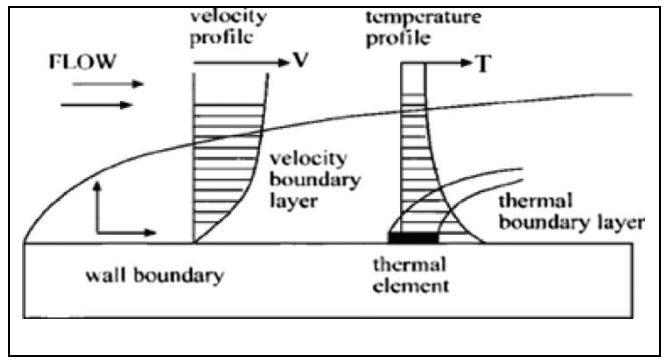
ME 3304: HEAT & MASS TRANSFER
CHALLENGE-BASED WORKSHOP #3:
INTRODUCING BOUNDARY LAYERS

STEP 2:GATHERING PERSPECTIVES AND RESOURCES
STEP 3: RESEARCH AND REVISE

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

Boundary Layers

Boundary layers form in fluids next to solid surfaces as a function of the geometry and fluid motion. They represent the thermal resistance in the fluid between the surface and the free stream temperature of the fluid. The thermal boundary layer thickness is the distance from the body at which the temperature is 99% of the temperature found in the free stream.



Heat Transfer Coefficient

The heat transfer coefficient is defined as:

$h_x = q'' / (T_{plate} - T_{air})$

The heat transfer coefficient represents the conduction of heat through the boundary layer next to the surface. Consequently, the heat transfer coefficient will be proportional to the thermal conductivity of the fluid (kf) and inversely proportional to the thermal boundary layer thickness δ:

$h_x \sim k_f / \delta$

Thermal Resistance

The thermal resistance of the boundary layer is the inverse of the heat transfer coefficient.

$R'' = 1 / h_x$

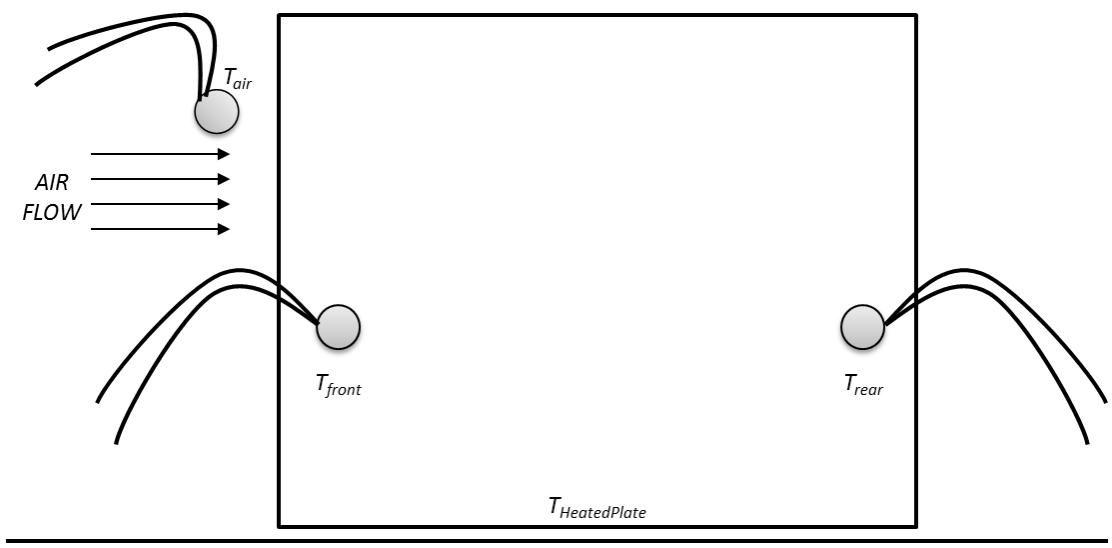
Consequently, the resistance increases as the boundary layer becomes larger for a given fluid thermal conductivity.

ME 3304: HEAT & MASS TRANSFER
CHALLENGE-BASED WORKSHOP #3:
INTRODUCING BOUNDARY LAYERS

STEP 2:GATHERING PERSPECTIVES AND RESOURCES
STEP 3: RESEARCH AND REVISE

STEP 3: RESEARCH AND REVISE

- A preliminary sketch of the plate and temperature sensors is provided below. Complete the sketch to illustrate the setup that your team will use to answer the Challenge Question. (i.e., where should the heat flux sensors be placed?)



How will your team determine the heat transfer coefficient?

- Provide the equation(s) you will use. State which variables you will be able to measure, and how they will be measured.

Update your hypothesis as needed given the information you gained in Step 2.

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ME 3304: HEAT & MASS TRANSFER CHALLENGE-BASED WORKSHOP #3: INTRODUCING BOUNDARY LAYERS
STEP 4:TEST YOUR METTLE

The following video shows you the experimental setup and procedure required for temperature and heat flux measurements.

Video 7: "Workshop 3"

Follow along and answer the questions on the provided worksheet. Use the above video to assist you. Do not click finish button until you are finished and no longer need to use the video.

ME 3304: HEAT & MASS TRANSFER
CHALLENGE-BASED WORKSHOP #3:
INTRODUCING BOUNDARY LAYERS

STEP 4:TEST YOUR METTLE

Your goal is to see how plate thickness affects the heat transfer from surfaces.

EXPERIMENTAL SESSION

- Watch the provided video.
- Orient the fan parallel to the plate.
- Turn on the fan, and ONCE AGAIN, feel the temperature across the thick and thin plates with the air blowing across them.

Evaluate the Results:

- Using the provided data, calculate the heat transfer coefficients at the front and back of plates:

Air Temperature =						
	Front Temp (^oC)	**Back Temp (^oC)**	**Front q" (W/m^2)**	**Back q" (W/m^2)**	**Front h (W/m^2-K)**	**Back h (W/m^2-K)**
Thin Plate						
Thick Plate						

Examine the data that you collected and the heat transfer coefficient you calculated for each orientation. As you work towards answering the Challenge Question, answer the following questions:

- How does the boundary layer affect the measured value of the heat transfer coefficient?

- Which part of the plate has the largest thermal resistance to the air?

- What does this indicate about the thickness of the thermal boundary layer in the air?

- Explain the relative values of the heat transfer coefficient you measured for the different fan orientations.

- Plot the profile of heat transfer coefficient as a function of distance along a plate for the different arrangements.

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ME 3304: HEAT & MASS TRANSFER CHALLENGE-BASED WORKSHOP #3: INTRODUCING BOUNDARY LAYERS
STEP 5: REFLECTION

Discuss and answer the following questions:

15. How does the heat transfer coefficient change over the distance of a plate? Why?

16. Which plate yields the highest average heat flux? Highest average temperature?

3. Which plate should be used to cook the chicken evenly?

4. What did you learn? What do you know now, that you didn't know before?

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Workshop 4 (Information and videos on Qualtrics, questions answered on separate sheets)

ME 3304: HEAT & MASS TRANSFER
Challenge-Based Workshop #4:
Internal Flow

THE CHALLENGE

Objectives:

- Gain an understanding of convection heat transfer coefficients.
- Gain an understanding of fluid thermal resistance.
- Gain an understanding of the factors affecting heat transfer coefficients.
- Gain an understanding of the difference between heat flux and temperature.

Context and Challenge:

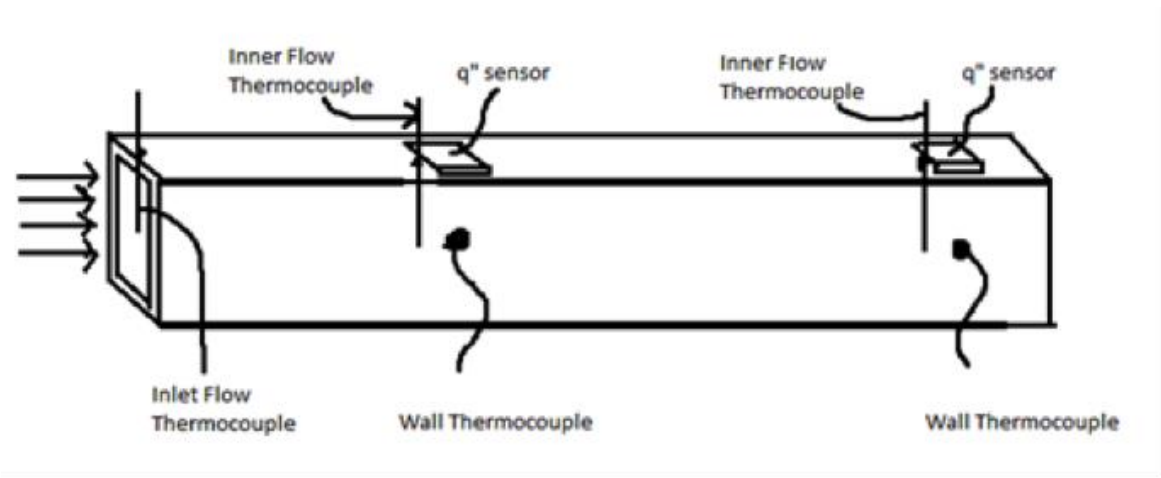
Your manager has an idea to cool a stream of gas using some aluminum square channels that are available. He wants you to size the system and evaluate its thermal performance. The channels are one-inch square outside dimensions, with a 1/16 inch wall thickness. Your challenge is to determine the mass flow rate to control the exit temperature to 40°C.
Specifically, answer the following Challenge Question:

Challenge Question:
Based on your measurements, how will you determine the mass flow rate to control the flow temperature to 40°C at the channel exit?

Available Equipment:

Use the instrumentation supplied to investigate how convection affects the outlet temperature. In your laboratory, you have access to:

- A thin-walled channel, which has *thermocouple* and *heat flux* sensor pairs attached along the length of the channel.
- *Thermocouples* have been inserted into the flow at the inlet and also at various positions along the channel.
- A heat gun supplies the heated flow of air.
- Video software to follow along with and



ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #4:
INTERNAL FLOW

STEP 1: GENERATE IDEAS

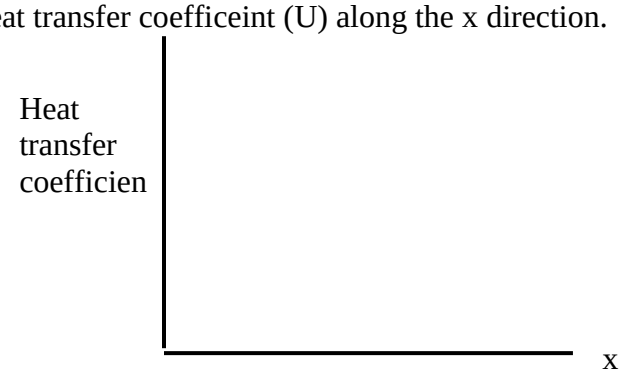
The goal of this phase is to establish a hypothesis for the channel operation.
As a team, discuss the following questions

- Identify the heat source and the heat sink from the challenge description.

- On the graph below sketch the variation of the flow temperature (T_{flow}), channel wall temperature (T_{wall}) and the outside temperature ($T_{outside}$) along the x direction.

- On the graph below sketch the variation of the heat flux from the fluid to the wall along the x direction.

- On the graph below sketch the variation of heat transfer coefficient of the flow on the inside of the channel (h_{inside}) , heat transfer coefficient of the flow on the outside ($h_{outside}$) and the overall heat transfer coefficeint (U) along the x direction.



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ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #4:
INTERNAL FLOW

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH AND REVISE

For flows inside of a conduit, the fluid temperature changes as the thermal energy is transferred into or out of the fluid. Moreover, the thickness of the fluid boundary layer is limited by the internal size of the structure. The flow can be either laminar or turbulent. The criterion is based on the Reynolds of the flow using the diameter of the tube as the length scale. The usual range for transition from laminar to turbulent flow is between Reynolds numbers of 2,000 and 10,000 for this particular case.

An energy balance on the flow can be used to relate the rate of enthalpy change of the fluid with the heat flux from the fluid into the wall

$$\dot{m}C_p \frac{dT_{flow}}{dx} = q''P$$

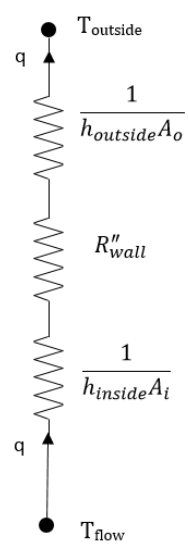
where $\dot{m}$ is the mass flow rate of the fluid and P is the perimeter of the channel. In terms of a uniform temperature heat sink $T_{outside}$, the temperature distribution is

$$\frac{T_{flow} - T_{outside}}{T_{inlet} - T_{outside}} = exp\left(-\frac{UP}{\dot{m}C_p}x\right)$$

The overall heat transfer coefficient is defined as

$$U_o = \frac{q''_{outside}}{T_{flow} - T_{outside}} = \left[\frac{1}{h_{outside}} + R''_{wall} + \frac{1}{h_{inside}}\left(\frac{A_o}{A_i}\right)\right]^{-1}$$

The following diagram shows the resistance analogy in calculating the overall heat transfer coefficient



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Note that the heat flux is measured on the outside of the channel. Consequently, because the heat transfer on the inside and outside of the channel must be the same, the area difference must be included $q = A_i q''_{inside} = A_o q''_{outside}$

where $A_i = L \cdot$ Inside perimeter and $A_o = L \cdot$ Outside perimeter. The heat transfer coefficients will be in terms of the inside and outside fluid temperatures

$$h_{inside} = \frac{q''_{inside}}{T_{flow} - T_{wall}} \quad , \quad h_{outside} = \frac{q''_{outside}}{T_{wall} - T_{outside}}$$

- Evaluate the thermal resistance of the wall. The thermal conductivity of aluminum is k = 175 W/m-K. Is this resistance significant for heat transfer coefficients less than 100 W/m^2-K? What is the non-dimensional ratio of the wall resistance to the convective resistance?

- Sketch the simplified the resistance network diagram based on your response to the previous question?

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Followed by Video 8: "Workshop 4" on Qualtrics

Watch film and perform experiment before moving on.

Watch film and perform experiment before moving on.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #4:
INTERNAL FLOW

STEP 4: TEST YOUR METTLE

The following data corresponds to the measurements made on the channel described in the challenge. An axial flow fan is used to circulate air on the outside of the channel. Calculate the missing values in the table below. The thermal conductivity of aluminum is k = 175 W/m-K. The outside air temperature is 25°C.For your calculations use the density of air as 0.97kg/m^3 and C_p as 1000J/kgK.

High Fan: Velocity= 11m/s

Location	$q''_{outside}$ (W/m²)	T_{flow} (°C)	T_{wall} (°C)	h_{inside} (W/m²K)	$h_{outside}$ (W/m²K)	U_o (W/m²K)
X=0.015m	1400	68	59			
x=0.3m	730	64	40			
x=0.6m	750	58	37			
x=0.9m	550	53	35			
x=1.2m	450	49	34			

$\dot{m}$ = q = average $q''_{outside}$ =

- Is the heat transfer coefficient uniform on the inside of the channel within the experimental uncertainty? Why or why not?

- How does the average $q''_{outside}$ value compare to the individual measured $q''_{outside}$ values?

- Calculate the mass flow ($\dot{m}$) rate required to reach an internal flow temperature of 40°C. The inlet flow temperature is 70°C . The channel is 1.2m long and has one-inch square outside dimensions, with a 1/16 inch wall thickness. Use the average overall heat transfer coefficient is 20 W/m^{2}K. The outside temperature is 25°C.

$\dot{m}$ =

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ME 3304: HEAT & MASS TRANSFER

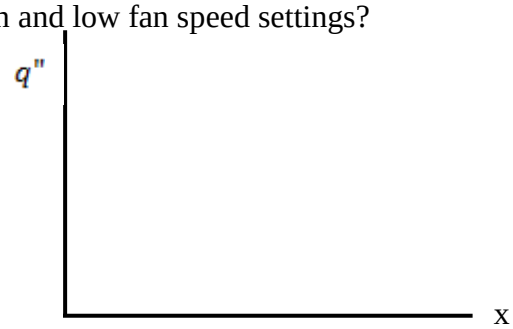
CHALLENGE-BASED WORKSHOP #4:
INTERNAL FLOW

STEP 5: REFLECTION

1. How does mass flow rate affect the overall heat transfer and the overall temperature of the fluid?

2. How does the flow temperature (T_{flow}), channel wall temperature (T_{wall}) and the outside temperature ($T_{outside}$) vary along the x direction? Why do the values change as observed?

3. How does the heat flux from the fluid to the wall vary along the x direction for the high and low fan speed settings?



4. How does the the overall heat transfer coefficeint (U) compare to the heat transfer coefficient on the flow on the inside of the channel (h_{inside}) and the heat transfer coefficient on the flow on the outside ($h_{outside}$) ?

5. What did you learn? What do you know now that you didn't know before?

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Workshop 5 (No Qualtrics or videos. Entire workshop filled out on paper)

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #5:
PARALLEL AND SERIES RESISTANCES

THE CHALLENGE

Objective:

- Gain an understanding of the difference between parallel and series thermal resistances.
- Gain an understanding of the difference between heat, energy, and temperature.
- Gain an understanding of the difference between heat flux and temperature measurements.

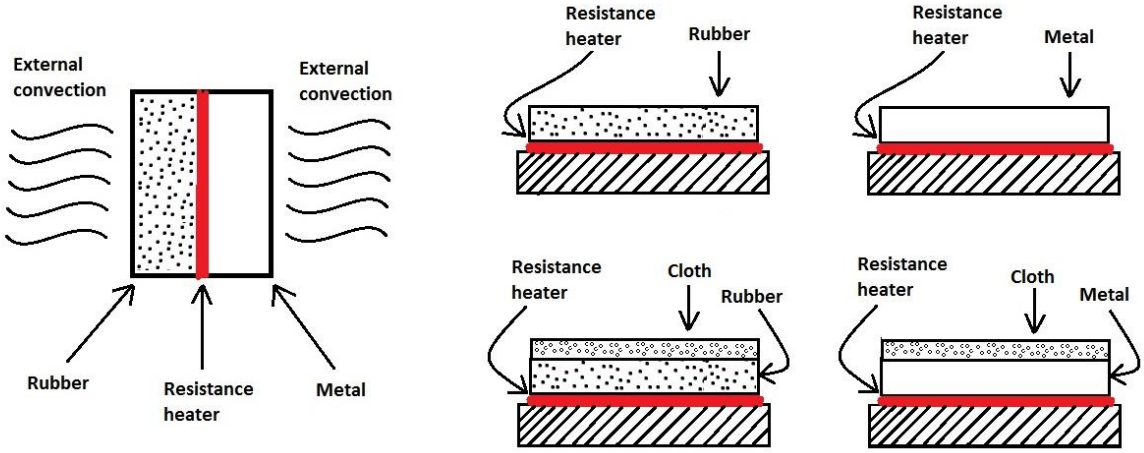
Context and Challenge:

Metal buildings are typically made with steel beams with layers of thermal insulation placed in between in assembling the roofs and walls. The insulation works well except where the beams are, which act like thermal conduits. Some manufacturers cover the beams and insulation with a layer of cloth. There is a dispute whether this affects the thermal performance of the walls and roofs. You are to resolve this dispute. Does the cloth matter or not? You need to justify your response.

Challenge Question:

What effect does adding cloth have on metal vs. insulation?

Below are the five configurations you will be working with. The first configuration will involve measuring heat flux on the sides of the plates exposed to the external convection. The other two configurations will involve measuring heat flux on the surface of the rubber and metal plates. Measurements will also be performed to monitor the difference in heat flux measurements if a cloth were placed on both the rubber and metal plates on the right.



ME 3304: HEAT & MASS TRANSFER

WORKSHOP #5:
PARALLEL AND SERIES THERMAL RESISTANCES

STEP 1: GENERATE IDEAS

The goal of this phase is to establish a hypothesis for the expected behavior of the metal.
As a team, discuss the following questions.

- For each configuration on the previous page, label which ones involve parallel resistances and which involve series resistances.

- How will the heat flux readings differ for each configuration?

- How will surface temperature readings differ?

- Sketch **system diagrams** AND **resistance diagrams** for all five setups. Describe how you will expect the different materials will feel based on the relative resistances and how the resistances are combined (series vs. parallel). Utilize the TA's to help with this step.

ME 3304: HEAT & MASS TRANSFER

WORKSHOP #5:
PARALLEL AND SERIES THERMAL RESISTANCES

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH & REVISE

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

Thermal Resistance

Thermal resistance is a measure of the resistance of a material to heat transfer. At steady state it is proportional to the thickness of the material divided by the thermal conductivity. The general definition for thermal resistance is

$$Steady\ State\ resistance: \quad R'' = \frac{\delta}{k}$$

This can be used with the data and with the analysis to compare measured versus theory.

In the first workshop (#1) you used transient heat flux and temperature measurements to qualitatively determine the thermal conductivity of two materials. Now you have the additional background to actually determine values of thermal conductivity.

STEP 3: RESEARCH AND REVISE

- Using your resistance diagrams from the previous step, write energy balances for all five setups. Substitute R" into your equations so that they are all in terms of thermal resistance.

ME 3304: HEAT & MASS TRANSFER

WORKSHOP #5:
PARALLEL AND SERIES THERMAL RESISTANCES

STEP 4: TEST YOUR METTLE

Theoretical Calculations

You will first calculate Resistances of the materials from their properties. Use the definition of thermal resistance and the provided values to calculate the individual resistances of the three materials:

	Metal plate	Rubber	cloth
Thickness: δ (mm)	4.8	3.2	.25
Conductivity: k (W/mK)	237	.15	.04
Resistance: R" (m^2K/W)			

- Now use the above values to determine the parallel and series equivalent resistances (R_{eq}) for the five configurations:

	Series: Metal	Series: Metal+Cloth	Series: Rubber	Series: Rubber+Cloth	Parallel
R_{eq} (m^2K/W)					

Measured Values

- Evaluate the materials' response to heat flux. Before moving on, go to both the series and parallel setups, feel the different plates, and observe the temperature measurements.
- Use Fourier's law and your energy balances along with the heat flux and Temperature values provided to calculate measured resistance values and compare them with the calculated values.

Parallel				
Temperature (degC)			Heat Flux (W/m^2)	
Heater: 48	Metal: 41	Rubber: 39	Metal: 1100	Rubber: 600

First solve for the individual Resistances for metal and rubber, then use those to find R_{eq}

Using the values provided from the series circuits, calculate the equivalent resistances for each case:

Series				
	Metal	Metal+cloth	Rubber	Rubber+cloth
Heater Temp	56	56	56	56
Surface Temp	53	48	49	49
Surface q"	450	380	310	310
R_{eq}:				

STEP 4: TEST YOUR METTLE

Compare these equivalent resistances with the calculated ones.

ME 3304: HEAT & MASS TRANSFER

WORKSHOP #5:
PARALLEL AND SERIES THERMAL RESISTANCES

STEP 5: REFLECTION

Discuss and answer the following questions:

- Does adding the cloth change the total equivalent resistance more for the metal or the rubber? What is the difference in how the materials feel before and after adding the cloth?

- Estimate the value of the thermal contact resistance between the different materials.

- What does contact resistance seem to affect most in the experiment?

- In this experiment, we did not discuss the resistance due to convection. Given a heat transfer coefficient of $h=40W/m^2K$ blowing across each surface, calculate this resistance and new equivalent resistances. How does this resistance effect the five configurations?

- What did you learn? What do you know now, that you didn't know before?

Workshop 6 (All Sheets On Worksheets, Video on Qualtrics)

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
RADIANT HEAT TRANSFER

THE CHALLENGE

Objective:

- Gain an understanding of radiant heat transfer
- Gain an understanding of radiation view factors
- Gain an understanding of the effects of surface emissivity and absorptivity

Context and Challenge:

You are to evaluate an infra-red heater for a new process to heat pieces of sheet metal. The first question is how the surface properties of the sheet metal affect the heat transfer. To answer this question one is painted with a high emissivity paint ($\varepsilon = 1$) while the second is left plain metallic. It is desired to provide a radiation heat flux to the metal sheet of 100 W/m^2. Can this be achieved and how?

The next question is how do the properties of the heater affect the heat transfer. Two heaters are compared – one is painted with a high emissivity paint ($\varepsilon = 1$) while the second is left unpainted and gray.

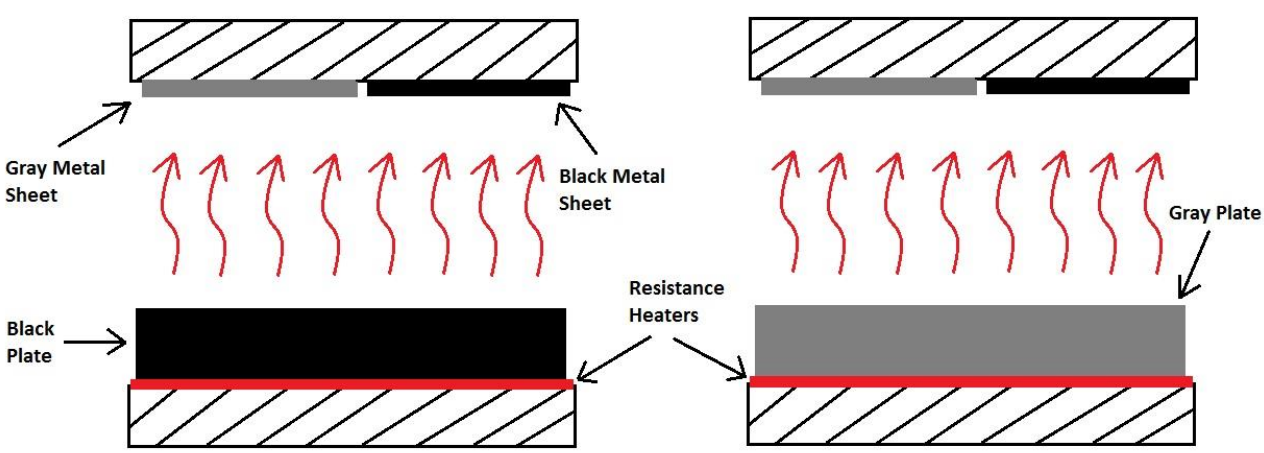
Challenge Question:

Can you use the infra-red heater to process the metal sheets?

Available Equipment:

You are provided with a 12.7cm by 12.7cm heated plate that is painted black. There is also a piece of insulation with two 5.08cm by 5.08cm pieces of sheet metal. Thermocouples are attached to the surface of all of the plates.

Draw and label a control volume around the heated plates below (neglect convection). How do they differ?



ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
RADIANT HEAT TRANSFER

STEP 1: GENERATE IDEAS

The goal of this section is to establish a hypothesis for how the infra-red heater operates and interacts with the metal sheets.

As a team, discuss the following questions:

- How does the surface emissivity of the heater plate affect the thermal radiation?

- How does the surface absorptivity of the receiver plates affect the thermal radiation?

- What is the relation between absorptivity and emissivity?

- Which setup from the diagram on the previous page will yield the highest heat transfer? Why?

- What is the effect of different separation distances on the radiation from the heated plate to the receiver plates?

Next, frame your **hypothesis:**

- How do you propose to determine the effects of surface properties and arrangement on the calculated heat flux to the sheets?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
RADIANT HEAT TRANSFER

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH & REVISE

The black body emissive power from a surface is given as

$$E_b = \sigma T^4 \tag{1}$$

where the Stefan-Boltzmann constant is $\sigma = 5.67 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m^2K^4}}$ and the temperature is in absolute Kelvin.

The heat flux that is actually emitted from a surface E is proportional to the emissivity of the surface

$$E = \varepsilon E_b = \varepsilon \sigma T^4 \tag{2}$$

The same is true for the radiation that is absorbed on a surface relative to the irradiation G (the radiation coming to a surface)

$$G_{absorbed} = \alpha G \tag{3}$$

where α represents the absorptivity of the surface. For gray and black surfaces Kirchoff's law applies

$$\alpha = \varepsilon \tag{4}$$

The absorptivity is equal to the emissivity! Consequently, the net radiation energy balance into a surface is simply what is absorbed minus what is emitted.

$$q''_{netin} = \alpha G - \varepsilon E_b = \varepsilon(G - E_b) = G - J \tag{5}$$

where the radiosity is defined as

$$J = \varepsilon E_b + \rho G \tag{6}$$

When the two surfaces are black, the resulting radiation exchange between them is

$$\frac{q_{12}}{A_2} = F_{21}(E_{b1} - E_{b2}) \tag{7}$$

where F_{12} is the view factor from surface 1 to surface 2 and $A_1F_{12} = A_2F_{21}$ by reciprocity. The view factor represents the fraction of energy leaving one surface that is intercepted by the other surface. Consequently, it is very dependent on the distance between the two surfaces and has values between zero and one.

This is followed by Video 9: "Workshop 6" on Qualtrics

Watch film and perform experiment before moving on.

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
RADIANT HEAT TRANSFER

STEP 4: TEST YOUR METTLE

Make sure to put your hand close to the gray and black plates to feel the difference. DO NOT TOUCH the plates. They are VERY hot. At each distance use the measurements from the black sheet to find the view factor value, F_{12} . Assuming that the view factor is the same for the non-painted surface, determine its emissivity.

Use the measurements from the black heater and sheet to find the view factor value, F_{12} .

Below you are given values of heat flux that have been calculated using the temperature change over time for the two sheets. The lumped capacitance equation was used as described in the video. The temperature of the heated plate was T_1 = 78°C and the receiver plate was T_2 = 23°C.

Heater (1)	Sheet (2)	Measured q″ for Test 1 (L=10.5cm)	Measured q″ for Test 2 (L=7cm)
Black	Black	80.9 W/m^2	155 W/m^2
Black	Gray	32.3 W/m^2	72 W/m^2
Gray	Black	---	97 W/m^2
Gray	Gray	---	65 W/m^2

If you assume that all of the surroundings are at the same temperature as T_2 = 23°C, the exchange with the heater provides all of the net heat transfer to the receiver plates. Based on this, find the corresponding value of view factor for the two distances.

E_{b1} =

E_{b2} =

F_{21} (calculated using Test 1 at L=7 cm) =

F_{21} (calculated using Test 2 at L=10.5 cm) =

Why are they different?

What is the irradiation of the heater (surface 1) assuming black surfaces provide the irradiation at room temperature? G_2 =

Find the radiosity of the gray heater (surface 1) assuming an emissivity of ε_1 = 0.45 and reflectivity of ρ_1 = 0.55, J_1 =

Why and how is this different from the black body emissive power for the gray heater (surface 1)?

Find the heat flux from gray heater to the black plate by using J_1 in place of E_{b1}, q_{12}/A_2 =

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
RADIANT HEAT TRANSFER

STEP 4: TEST YOUR METTLE

Examine your results and calculations. As you work towards answering the Challenge Question, answer the following questions:

- How do your results compare between Test 1 (L=10.5 cm) and Test 2 (L=7 cm)?

- How can you achieve the required net heat flux of 100 W/m^2 to the receiver plate (surface 2)?

- Are your values of view factor F_{21} reasonable?

- Do you believe how much difference the surface coating makes on the resulting radiant heat flux? Why?

ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #6:
RADIANT HEAT TRANSFER

STEP 5: REFLECTION

Discuss and answer the following questions:

1. How does the gray heater feel different than the black heater at the same temperature? Why is this?

2. For the temperature range used were the values of heat flux from radiation more or less than those you previously measured from convection? Which method is more efficient at transferring heat over this temperature range?

3. Why did we neglect the radiation between the room and the metal sheets during these tests?

4. What did you learn? What do you know now, that you didn't know before?

Appendix C: All Concept Questions (Given on Tests, Quizzes and Concept Inventory)

- Questions 1-5 were given as the initial concept quiz before the first semester
- Questions 1-19 were given as final concept test at the end of the first semester
- Questions 10, 20-22, 24, 16, 17, 25 and 26 were given as the first of 5 problems on the final exam in the second semester
- Question 27 was given on quiz 3 of the second semester
- Question 28 was given on quiz 6 of the second semester
- Question 29 was given on quiz 7 of the second semester
- Question 30 was given on quiz 11 of the second semester
- Questions 14, 15, and 31-33 were given as the first of 5 problems on the first test in the second semester
- Questions 34-38 were given as the first of 5 problems on the second test in the second semester
- Questions 1, and 39-44 were given to all of the first semester's previous heat transfer students the following year to gauge the retention of their conceptual understanding.
- Answers to questions are highlighted in blue

1. An engineering student walking barefoot (without shoes or socks) from a tile floor onto a carpeted floor notices that the tile feels cooler than the carpet. Which of the following explanations is the most plausible way to explain this observation?

a. The carpet has a slightly higher temperature because air trapped in the carpet retains energy from the room better.
b. The carpet has more surface area in contact with the student's foot than the tile does, so the carpet is heated faster and feels hotter.
c. The tile conducts energy better than the carpet, so energy moves away from the student's foot faster on tile than carpet.
d. The rate of heat transfer into the room by convection (air movement) is different for tile and carpet surfaces.
e. The carpet has a slightly higher temperature because air trapped in the carpet retains more energy than the tile floor.

2. Two identical closed beakers contain equal masses of liquid at a temperature of 20°C. One beaker is filled with water and the other with ethanol (ethyl alcohol). The temperature of each liquid is increased from 20°C to 40°C using identical heaters immersed in the liquids. Each heater is set to the same power setting. It takes 2 minutes for the ethanol temperature to reach 40°C and 3 minutes for the water temperature to reach 40°C. Ignoring evaporation losses, to which liquid was more energy transferred during the heating process?

a. Water because it is heated longer.
b. Alcohol because it heats up faster (temperature rises faster)
c. Both liquids received the same amount of energy because they started at the same initial temperature and ended at the same final temperature
d. Can't determine from the information given because heat transfer coefficients from the water and alcohol beaker surfaces are needed
e. Can't determine from the information given because heat capacities of water and ethanol are needed
f. Water because it has a higher boiling point than ethanol

3. On a very cold winter day, a group of engineering students notices that quickly licking the metal end of an ice scraper left outside overnight caused their tongues to freeze to the metal surface. However, a quick lick of the plastic handle of the scraper didn't cause any freezing to occur. How can you explain this observation?

a. Metal is colder than plastic because it transfers energy to the atmosphere faster
b. Metal is colder than plastic because metal is more dense and therefore retains cold better
c. Metal is colder than plastic because plastic stores energy better
d. Metal conducts energy better than plastic, so energy moves away from the tongue faster when touching metal

4. You have a glass of tea in a well-insulated cup that you would like to cool off before drinking. You also have 2 ice cubes to use in the cooling process and have access to an ice crusher. Assuming no energy is lost from the tea into the room and no ice is lost in the crushing process, which form of ice (cubes or crushed ice) added to your tea will give a lower drink temperature?

a. the crushed ice
b. the ice cubes
c. either will lower the drink temperature the same amount
d. can't tell from the information given

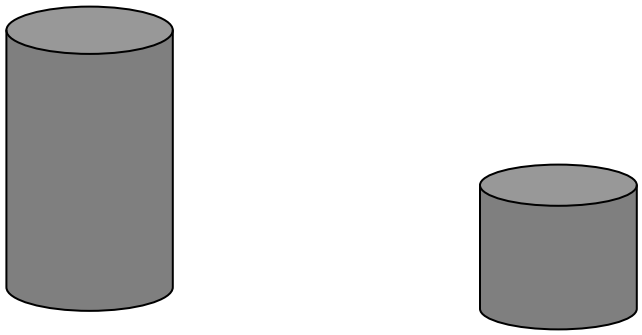
5. Your answer to question 4 is correct because:

a. Crushed ice has more surface area so the energy transfer rate will be higher
b. Energy transfer is proportional to the mass of ice used
c. Crushed ice will melt faster and will transfer energy from the tea faster
d. Ice cubes contain less energy per mass than crushed ice so tea will cool more
e. Ice cubes have a higher heat capacity than crushed ice

6. Two identical thermometers at 25°C are placed in a room at that same temperature. An engineering student wraps one thermometer in a blanket and the other in aluminum foil wrap. What happens to the observed temperature readings of the two thermometers?

a. The thermometer in foil becomes noticeably cooler than the thermometer in insulation
b. The thermometer in insulation becomes noticeably cooler than the thermometer in foil
c. There is no noticeable difference in the thermometer readings

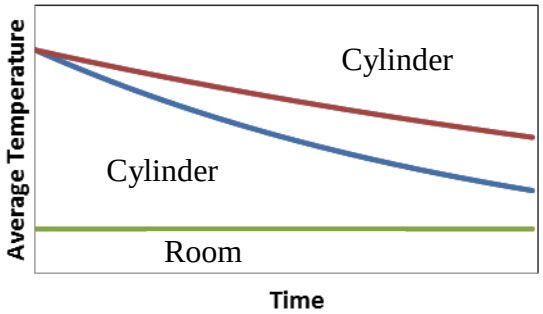
7. Two copper cylinders, each at 75°C, are allowed to cool in a room where the air temperature is 25°C. As shown below, cylinder 1 is taller than cylinder 2 but both cylinders are the same diameter. The top and bottom of each cylinder are perfectly insulated so the only heat loss is through the sides of the cylinders.



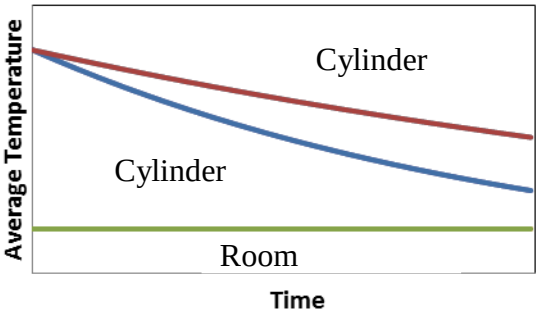
Cylinder 1 **Cylinder 2**

Which of the following four graphs would most closely approximate the average temperature of the two cylinders as a function of time?

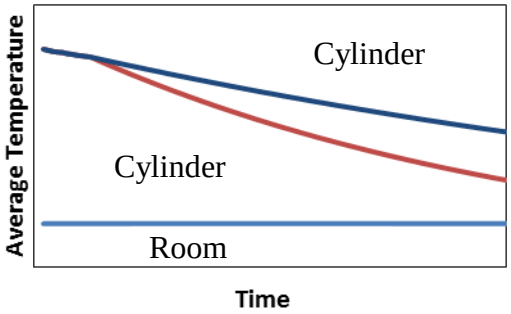
A



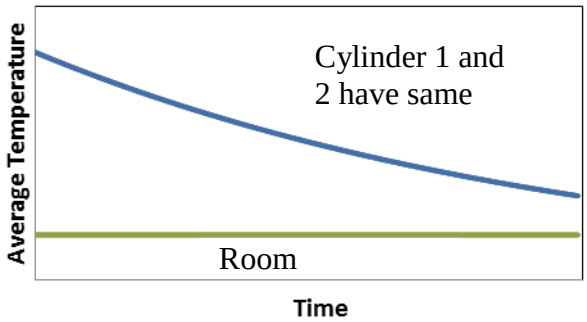
B



C



D



8. Please review the diagrams in Question 7. Your answer to Question 7 is correct because:

a. Cylinder 2 contains less mass and less stored energy so it will cool faster

b. Cylinder 1 has more heat transfer area in contact with the atmosphere and therefore will cool faster

c. Both cylinders will cool at the same rate because the surface area/volume ratio is the same for each

9. If 25°C (77°F) air feels warm on our skin, why does 25°C water feel cool when we swim in it?

a. When water contacts human skin, it vaporizes at the surface, which causes the water to feel cooler than air
b. Water holds energy better than air does, so air feels warmer since it is transferring energy faster
c. The heat transfer rate from skin to water is faster than the rate from skin to air because of the differences in fluid physical properties
d. Water opens pores in human skin better than air does, so the heat transfer area is larger with water

10. A person walks toward two diffuse grey surfaces that are maintained at 1000K.
Surface 1 has an emissivity of 0.90 and a reflectivity of 0.10
Surface 2 has an emissivity of 0.50 and a reflectivity of 0.50

Which statement is true?

a. The person will feel warmer as they approach surface 1 than surface 2
b. The person will feel warmer as they approach surface 2 than surface 1
c. The person will feel the same warmth in both cases
d. Not enough information given

11**. Rubbing alcohol feels cool when placed on your skin. This is *primarily* because:**

a. Alcohol remains cooler than room temperature even when stored for a long time
b. Alcohol deadens the nerves in your skin
c. Alcohol evaporates quickly
d. Alcohol has a higher heat capacity than the surrounding air

12**. A flat sheet of aluminum foil and a thicker aluminum baking sheet are placed in an oven at 400°F for a long period of time. While holding these objects from the oven, which feels hotter to the touch?**

a. Both objects feel equally hot because they are at the same temperature
b. The baking sheet feels hotter because it is hotter
c. The aluminum foil feels hotter because it is hotter
d. The baking sheet feels hotter because it has a higher mass

13. Two solid materials at 500 K and of identical dimensions and masses are exposed to identical environments to cool them. Material A and material B are physically identical except that material A has a heat capacity twice that of Material B.

Initially, which material cools faster in K/sec?

a. Material A, because it has a higher heat capacity
b. Material B, because it has a lower heat capacity
c. They cool at the same rate, because the initial temperature driving force is the same for both materials

Two solid materials are sitting at room temperatures. One has a low thermal conductivity (insulation) and the other has a high thermal conductivity (metal). Indicate the relative thermal response between the two materials when an identical hot block of copper is placed on each.

14. Which has the faster temperature rise at the surface?

    a. the low conductivity material
    b. the high conductivity material
    c. the two materials respond at the same rate

15. Which has the higher rate of heat flux at the surface?

    a. the low conductivity material
    b. the high conductivity material
    c. the two materials respond the same

Water at 20°C enters a pipe that is maintained at 50°C. The average temperature of the water exiting the pipe is 40°C at these conditions. If the mass flow rate of the water is doubled, what will happen to the following quantities? Assume that the heat transfer coefficient between the pipe and the water does not change.

16. The average temperature of the water at the exit will:

    a. Increase
    b. Decrease
    c. Remain the same

17. The overall heat transfer from the pipe to the water will:
    a. Increase
    b. Decrease
    c. Remain the same

18. You are in the business of melting ice at 0°C using hot blocks of metal as an energy source. One option is to use <u>one metal block</u> at a temperature of 200°C and a second option is to use <u>two metal blocks</u> each at a temperature of 100°C.

All of the metal blocks are made from the same material and have the same weight, surface area, and constant properties.

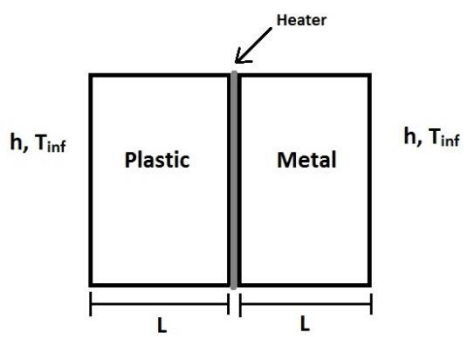
If the blocks are placed in insulated cups filled with ice water at 0°, which option will melt more ice?

    a. The two 100°C blocks
    b. The one 200°C block
    c. Either option will melt the same amount of ice
    d. Can’t tell from the information given

19. Your answer to Question 18 is correct because:

a. 2 blocks have twice as much surface area as 1 block so the energy transfer rate will be higher when more blocks are used
b. Energy transferred is proportional to the mass of blocks used and the change in block temperature during the process
c. Using a higher temperature block will melt the ice faster because the larger temperature difference will increase the rate of energy transfer
d. Higher temperature blocks contain more energy per mass of block than lower temperature blocks
e. The heat capacity of the metal is a function of temperature
f. Multiple blocks have more mass and therefore more energy than a single block

Questions 20-24 pertain to the sketch shown. A resistance heater is sandwiched between two plates of the same thickness, L. One is a high conductivity metal and the other is a low conductivity plastic. Both plates are exposed to the same external convective heat transfer coefficient at the same environment temperature. The heater is turned on and allowed to reach steady state.



20. How do the outside surface temperatures compare for the metal and plastic?

a. The surface temperature of the plastic will be higher.
b. The surface temperature of the metal will be higher.
c. Both Surface temperatures will be the same.

21. How do the values of heat flux through each material compare?

a. Heat flux through the metal will be higher
b. Heat flux through the plastic will be higher
c. Heat flux will be the same through each material.

22. Mark all of the reasons that justify your answers to questions 20 and 21.

a. The heat transfer coefficient on each surface is the same.
b. The heater provides the same heat flux to each material.
c. There is more thermal resistance through the plastic than the metal.
d. There is more thermal resistance through the metal than the plastic.
e. There is a larger temperature difference across the plastic than the metal.

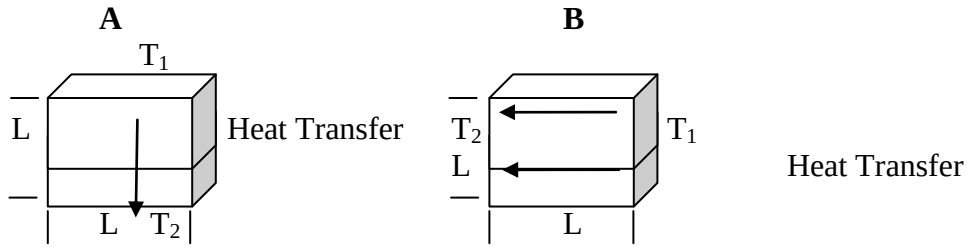
23. What happens to the surface temperatures of the plastic and metal when the value of the heat transfer coefficient is halved?

a. Both surface temperatures will increase by the same amount.
b. The plastic surface temperature will decrease and the metal surface temperature will increase.
c. The metal surface temperature will decrease more and the plastic surface temperature will increase.
d. The surface temperatures will remain unaffected by a change in the heat transfer coefficient.
e. Both surface temperatures will decrease.

24. What happens to the heat flux values through the plastic and metal plates when the heat transfer coefficient is halved?

a. The heat flux through each will decrease by the same amount.
b. The heat flux through metal will decrease more than through the plastic.
c. The heat flux through the plastic will decrease more than through the metal.
d. The heat flux through the materials remains unaffected by a change in h.

25. Two blocks of solid material have the same dimensions, but have very different thermal conductivities (one high and one low). Which arrangement of the blocks gives higher heat transfer (as indicated by the arrows) between the temperatures T_1 and T_2 at steady-state conditions? Note that the overall thickness (L) and area is the same for both arrangements.



a. Arrangement A has higher heat transfer than B
b. Arrangement B has higher heat transfer than A
c. Both arrangements have the same heat transfer

26. Your answer to Question 25 is correct because:

a. The thermal resistances always add
b. The heat transfer always adds
c. Heat transfer chooses the path of least thermal resistance

27. (off quiz 3 in second semester)

Indicate what would happen to the fin efficiency and fin heat transfer of an individual fin initially having a fin efficiency of 70% (increase, decrease, or no effect) if:		
	Fin efficiency	Fin heat transfer
a) convective heat transfer coefficient is increased	decrease	increase
b) the fin length is increased	decrease	increase

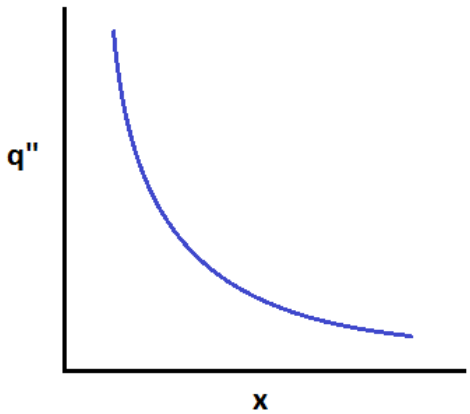
28. (off quiz 6 in second semester)
Quiz 6 – question 28 is part b of this quiz for purposes of this appendix
A general form for the local heat transfer coefficient h_x for a fluid flow of velocity V in the x-direction over a constant temperature surface is

$$Nu_x = C Re_x^m Pr^n$$

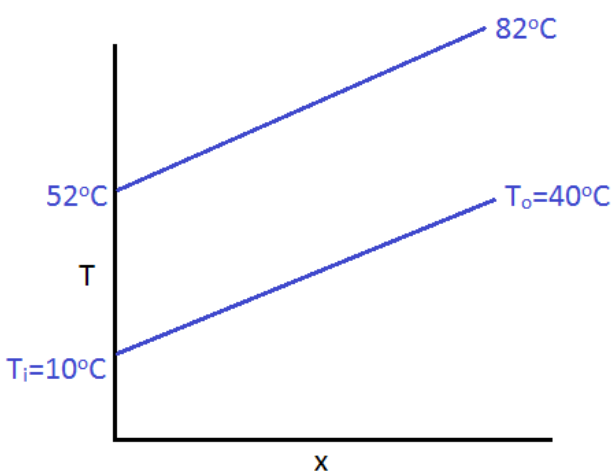
where C, m, and n are constants. Assume the fluid properties k, ρ, Pr, ν and C_p are constant and known. Based on this equation, show how to obtain the average heat transfer coefficient for a surface of width w and length L in the flow direction where

$$q = wL\overline{h_L}(T_{surface} - T_{flow})$$

a) (question 28) Sketch the heat flux from the surface from the surface as a function of x for $T_{surface} > T_{flow}$ with 0<m<1.



29. (off quiz 7 in second semester)
Quiz 7 question 29 is part e of this quiz for purposes of this appendix
A 10-cm diameter tube has an internal fluid mass rate of 1kg/s with a density of ρ=1000kg/m^3, kinematic viscosity, $\nu=10^{-6}$m/s^2, and specific heat of C_p=4000J/kg-K. The tube is 15m long. The bulk mean flow temperature changes linearly in distance along the tube from the intlet temperature of $T_i=10^oC$ to the exit temperature of $T_o=40^oC$. The heat transfer coefficient from the wall to thefluid is a constant h=600W/m^2-K.
e) Plot and label the temperature profiles of the wall and fluid as a function of x.



30. (off quiz 11 in second semester)
Quiz 11 (question 30 is part e of this quiz for purposes of this appendix)
Consider two black squares 0.2m on each side that are facing each other. The view factor from the surface of one to the other is 0.40. The surrounding room (also black) is at a temperature of 300K. The first surface (1) is maintained at a temperature of 600K and the second (2) at 400K.

d) If the spacing between the surface 1 and surface 2 is increased (changing the view factors), determine if q_{12} and q_1 increase, decrease, or remain the same. The temperatures remain the same.

q_{12}	Increase	Decrease	Remains the Same
q_1	Increase	Decrease	Remains the Same

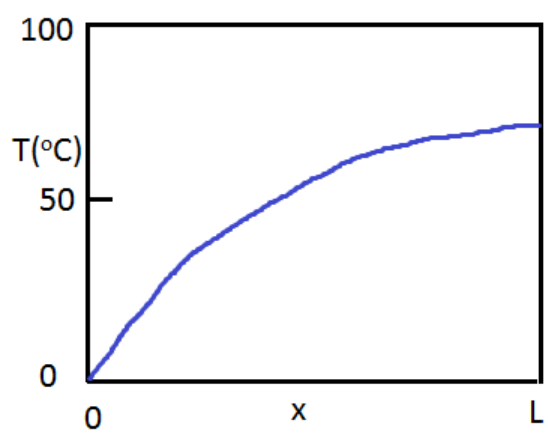
31. Consider the wall of a house on a cold day. The inside of the house is warm. The conditions are the same for Case A and Case B except that the heat transfer coefficient on the inside surface of the wall is higher for case A than case B. Which is true under steady-state conditions?

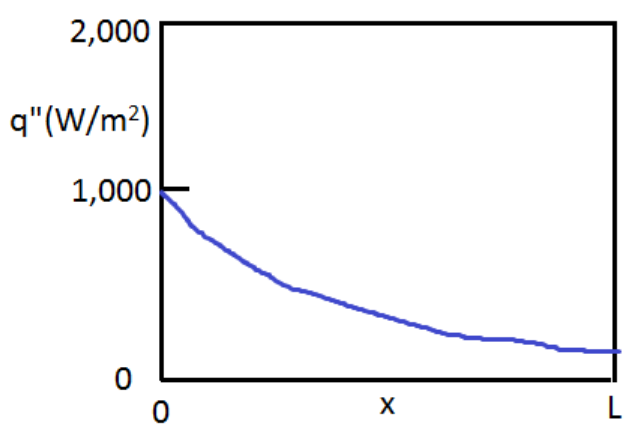
d. The inside surface temperature of the wall is higher for Case A than Case B.
e. The inside surface temperature of the wall is higher for Case B than Case A.
f. There is no difference in surface temperature.

32. Under the same conditions as question 31, which of the following is true?

d. The heat flux through the wall is higher for Case A than Case B.
e. The heat flux through the wall is higher for Case B than Case A.
f. There is no difference in heat flux through the wall.

33. A "straight" fin is mounted onto a wall that is maintained at 0°C. It has a convective heat transfer coefficient with the surrounding air of 10 W/m2-K at a temperature of 100°C. Neglect radiation and convection from the fin tip. Sketch the temperature and convective heat flux (to the fin) over it's length from x = 0 to x = L when the fin efficiency is 60%. Approximate the correct limiting values.





34. For internal flow through a channel with constant wall temperature that is higher than the fluid temperature, how will the outlet fluid temperature change if the specific heat of the fluid is increased while all other flow properties are the same?

d) Increase
e) Decrease
f) Remains the same

35. For internal flow through a channel with a constant wall temperature that is higher than the fluid temperature, how will the overall heat transfer change if the specific heat of the fluid is increased while all other flow properties are the same?

d) Increase
e) Decrease
f) Remains the same

36. For laminar external flow parallel to a constant heat flux flat plate, how does the surface temperature vary along the plate?

d) Increases with distance
e) Decreases with distance
f) There is no difference in surface temperature along the plate

37. Mark all of the correct reasons for your answer to number 36

g) The heat transfer coefficient is constant.
h) The boundary layer thickness increases with distance along the plate.
i) The heat transfer coefficient decreases with distance along the plate.
j) The heat transfer coefficient increases with distance along the plate.
k) The boundary layer thickness is constant.
l) The heat flux is constant so the temperature difference has to be constant.

38. If the diameter of a heated cylinder is increased, what is the impact on the heat flux from the exterior of the cylinder? Assume that the exterior fluid velocity (in crossflow) and all properties are the same and the cylinder temperature is the same.

d) Heat flux increases
e) Heat flux decreases
f) Heat flux remains the same

39. A person walks toward two diffuse grey surfaces that are maintained at the same very cold temperature of 100K. Assume that the room is at normal skin temperature (32°C) and has no net heat transfer effect to the person.

Surface 1 has an emissivity of 0.90 and a reflectivity of 0.10
Surface 2 has an emissivity of 0.10 and a reflectivity of 0.90

Which statement is true?

a. The person will feel warmer as they approach surface 1 than surface 2
b. The person will feel warmer as they approach surface 2 than surface 1
c. The person will feel the same warmth in both cases
d. Not enough information given

40. Two identical black (emissivity of 1.0) conductive plates are mounted onto a heat sink at 20°C. The other side of each is exposed to the same noon time sunlight. One of the surfaces experiences a strong wind with a large convection heat transfer coefficient while the other has a small convection heat transfer coefficient. The air temperature in both cases is the same (20°C). Which statement is true?

a. The plate with the smaller heat transfer coefficient conducts more thermal energy to the heat sink. Its top surface is at the same temperature as the other plate.
b. The plate with the smaller heat transfer coefficient conducts more thermal energy to the heat sink and its top surface is at a higher temperature than the other plate.
c. Both plates conduct the same thermal energy to the heat sink and are at the same temperature.
d. Both plates conduct the same thermal energy to the heat sink. The surface with the smaller heat transfer coefficient is at a higher temperature.
e. The plate with the higher heat transfer coefficient conducts more thermal energy to the heat sink. Its surface is at a lower temperature.

41. A piece of aluminum is sitting on a table next to a piece of NASA insulation. The aluminum has very high conductivity and the insulation has very low conductivity. You rub your hands together to warm them up and place one on each of the materials. Assuming your hands are at the same temperature right before touching the materials, which of the following is true?

a. The aluminum will have a faster temperature rise at the surface and lower surface heat flux than the insulation.
b. The aluminum will have a faster temperature rise at the surface and a higher surface heat flux than the insulation.
c. The aluminum will have a slower temperature rise at the surface and a lower surface heat flux than the insulation.
d. The aluminum will have a slower temperature rise at the surface and a higher surface heat flux than the insulation.
e. The aluminum and insulation will have the same temperature rise at the surface but the surface heat fluxes will be different.

42. Two metal blocks of equal size and mass are initially at room temperature (~20°C) and are then placed in a furnace operating at 300°C. Block 1 reaches a uniform temperature of 200°C in 5 minutes while block 2 takes 10 minutes to reach 200°C. To which block was more energy transferred during the heating process?

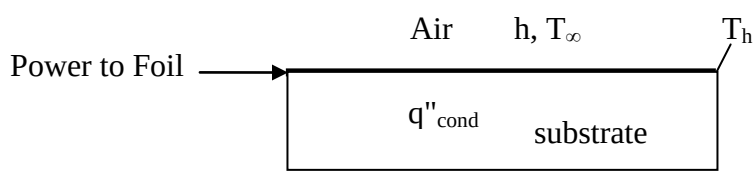
a. Block 2 because it is heated longer
b. Block 1 because it heats up faster (temperature rises faster)
c. Both blocks received the same amount of energy because they started at the same initial temperature and ended at the same final temperature
d. Can't determine from the information given because the heat transfer coefficient from the block surfaces is needed
e. Can't determine from the information given because heat capacities of the metals used to make the block are needed.

43. You have two identical, well insulated cups of hot tea at the same temperature. When you add two ice cubes, each with a mass of 48 g, to one cup of tea, the temperature of the tea after the ice cubes melt is 30°C. Consequently, how many ice cubes of mass 6 g will be required to cool the other cup to the same 30°C?

a. 8 because that gives the same total surface area of the ice cubes
b. 16 because that will give the same total mass of ice
c. 4 because each side of the 6 gram cube is scaled down by a factor of 1/2
d. Can't tell from this given information

44. A thin metal foil heater (0.1m by 0.1m size) is mounted on a substrate surface. The outer surface of the heater is exposed to air at a temperature of T_∞ = 20°C with a heat transfer coefficient of h = 10 W/m^2-K. If the foil is heated with 5 W of electrical power and the conduction heat flux from the heater to the substrate is 200 W/m^2, what is the steady-state heater temperature, T_h? Assume one-dimensional transfer and neglect radiation.

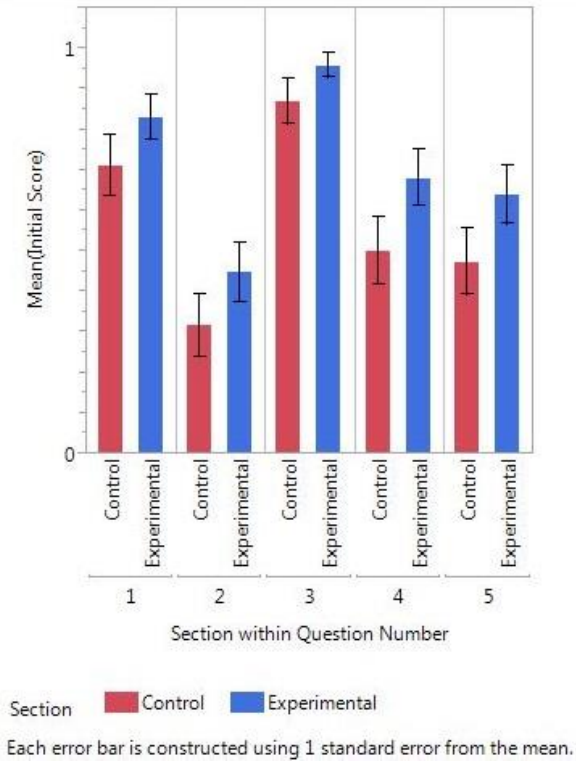
T_h = 50°C



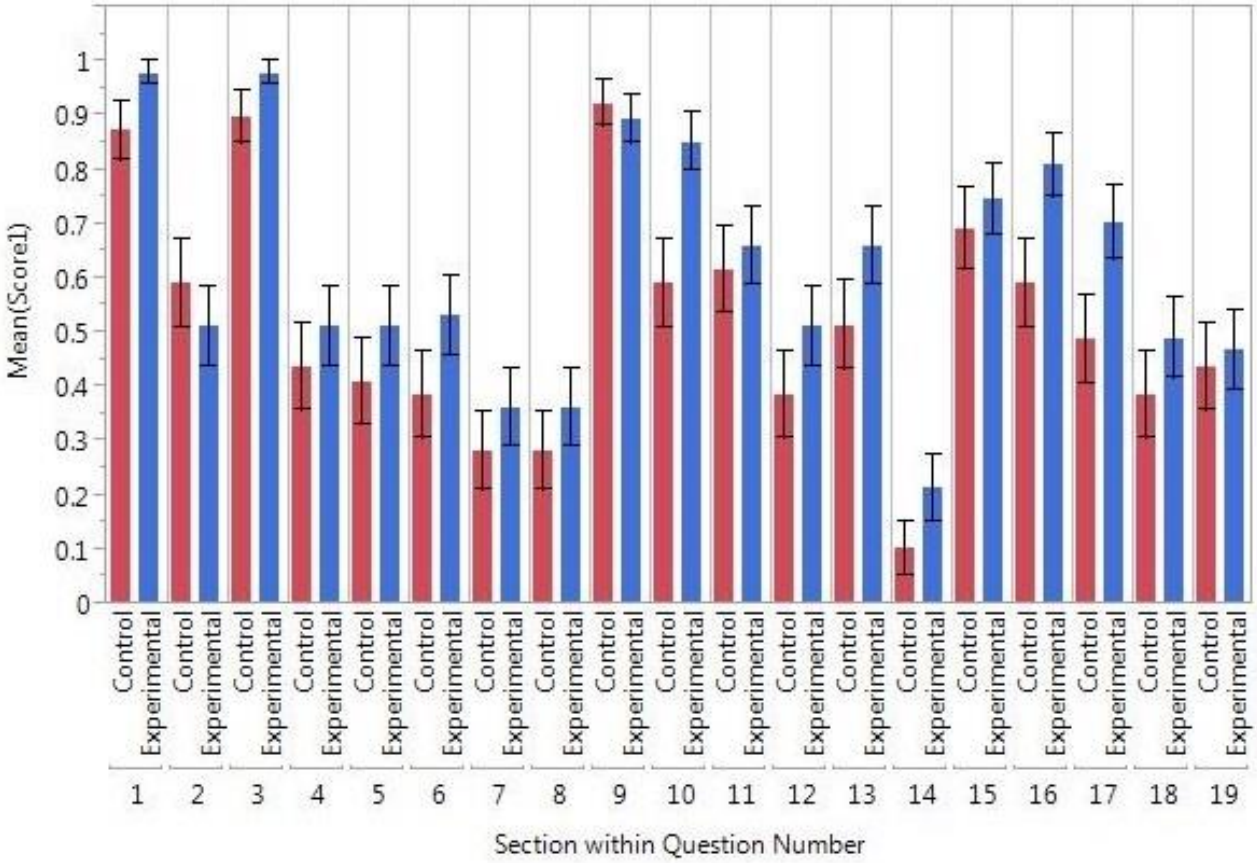
Appendix D: Concept Question Results

***Note: All question numbers correspond to those in Appendix C

Scores from initial concept quiz before first semester

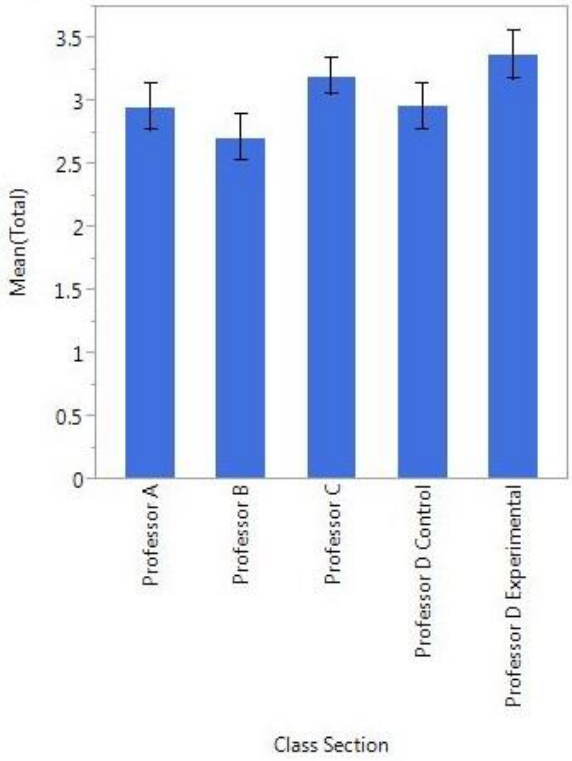


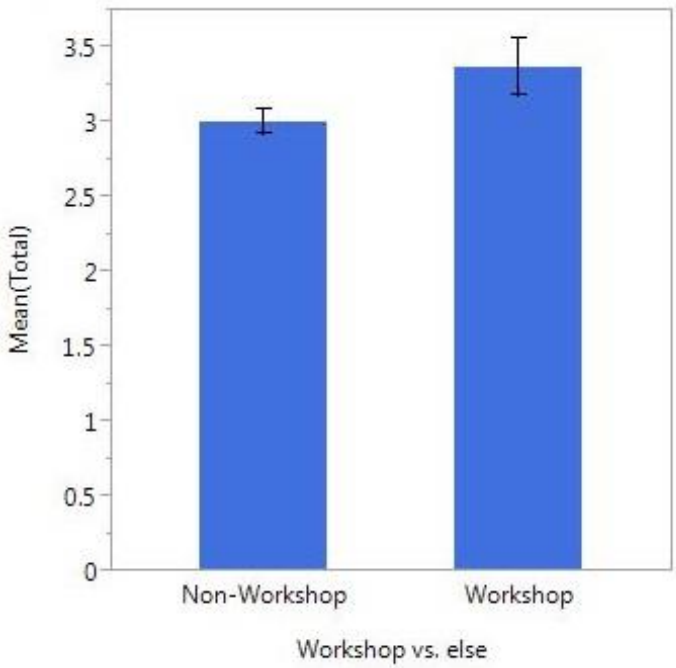
Scores from final concept test after first semester



Retention from first semester

- The following charts display the results of a seven question concept quiz given to all of the heat transfer students a few months after they finished their class to gauge their retention.
- The scores are first sorted by the different professors and then combined to show the experimental workshop students against all of the other heat transfer students. Most sections averaged about a 3 out of 7 on the quiz.





Second Semester

Quiz 3
Concept tested: fin heat transfer
Question analyzed

Indicate what would happen to the fin efficiency and fin heat transfer of an individual fin initially having a fin efficiency of 70% (increase, decrease, or no effect) if:		
	Fin efficiency	Fin heat transfer
a) convective heat transfer coefficient is increased		
b) the fin length is increased		

Results

	Experimental	Control
Part a	69%	80%
Part b	87%	83%

Quiz 6
Concept tested: External flow heat transfer
Question analyzed
Sketch the heat flux from the surface as a function of x for $T_{surf} > T_{flow}$ with $0<m<1$.
*Note: this question was asked after they were asked to give an expression for the average Nusselt number.
Results

Experimental	Control
72%	62%

Quiz 7
Concept tested: Internal flow temperature distribution
Question Analyzed
Plot and label the temperature profiles of the wall and fluid as a function of x.
*Note: internal flow constant heat flux on the wall
Results

	Experimental	Control
Partially Correct	44%	36%
Fully Correct	39%	26%

Quiz 11

Concept tested: Radiation heat transfer

Question Analyzed

If the spacing between surface 1 and surface 2 is increased (changing the view factors), determine if q_{12} and q_1 increase, decrease, or remains the same. The temperatures remain the same.

*Note: $T_{outside}$=300K T_1=600K T_2=400K

Results

	Experimental	Control
Part a correct	98%	89%
Part b correct	58%	50%
Completely correct	56%	50%

Test 1

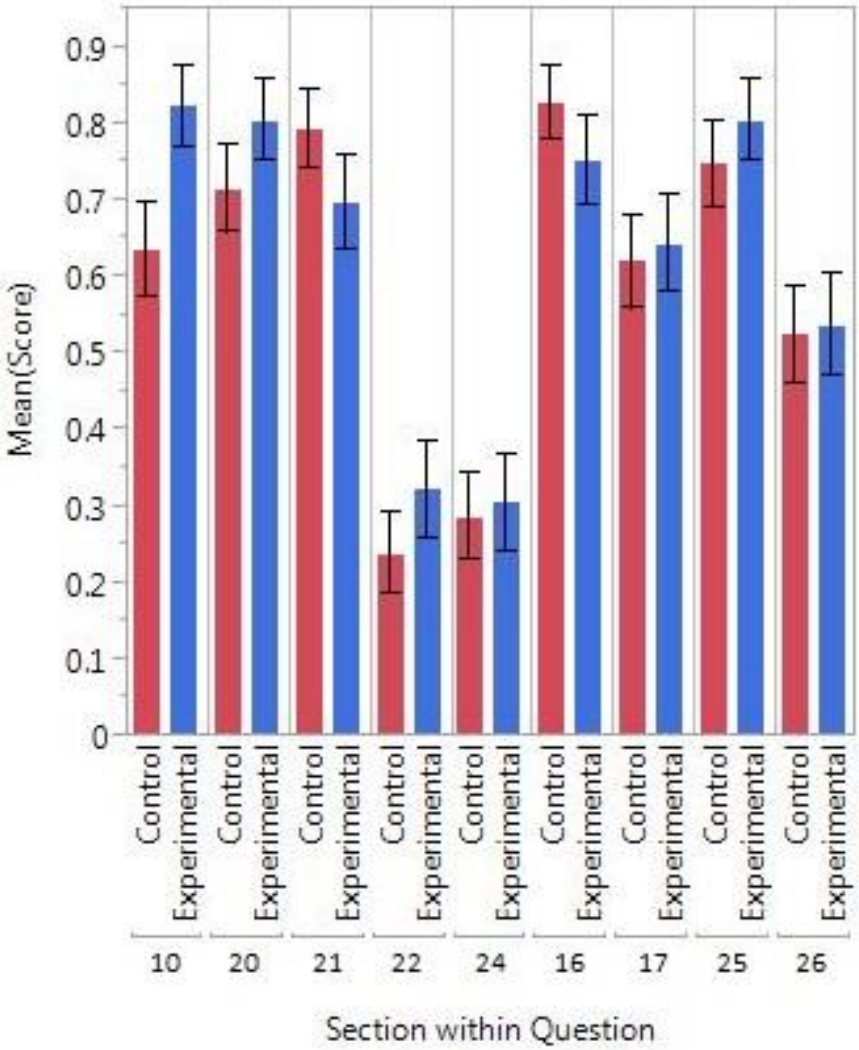
Question Number	Section	Initial Concept Quiz	First Test
14	Control	7.8%	20.3%
	Experimental	7.9%	72.3%
15	Control	75.0%	81.2%
	Experimental	68.3%	87.7%

Question Number	Experimental	Control
31	24.6%	39.1%
32	83.1%	59.4%
33 (Temperature)	84.6%	71.0%
33 (Heat Flux)	23.1%	10.1%

Test 2

	9AM	10AM
34	0.672131	0.784615
35	0.655738	0.861538
36	0.540984	0.630769
37	0.606557	0.507692
38	0.540984	0.553846

Second Semester Final Exam Concept Questions



Appendix E: Workshop Questionnaire Taken by the Students

WS Questionnaire

What was your overall impression of the workshop sessions related to your heat transfer course?
15/16 students said they were helpful in understanding the material.
"I felt like they were beneficial to my understanding of the material. They allowed us to see and feel what was going on."
"Definitely fixed some wrong intuitions about things"
"…helped us actually see what the transfer was rather than hear about it"
"At first I was upset that we had them, but after we did a few I realized that they were worth it. They helped me understand things better and made me think about the material more."

What did you like best about the workshop sessions?
Most students mentioned the hands-on aspect and being able to see what was covered in class.
One student: "we were able to feel the experimental setups and have conversations about that."
Another student mentioned liking the teamwork aspect the most.

What did you like the least about the workshop sessions?
Many different answers on this one. Some students mentioned that some of the questions asked in the workshops were unclear. A few students said there were too many calculations.

In your experience, how does the workshop class session compare to the lecture class session? Did you prefer one over the other as a learning environment? Why?
Most students mentioned that while they benefited from the workshops, they still believed the lecture was important for learning and introducing the material.
"I think having both together is very effective, as the workshop only made sense in context to what we learned in lecture."
"I'm glad we had the equations and knew what to expect beforehand"
"The workshop made me think more. In the class I was focused on making sure I had all of the notes, not necessarily understanding the material. The workshop helped to expand on the classroom section and get us thinking."

Did you feel that you learned the concepts related to heat transfer better in the lecture class sessions than in the workshop class sessions?
5/16 for workshop

What was your overall impression of the workshops and the workshop structure? What worked well in your opinion, and what could be improved upon?
Several students mentioned the ease and smoothness of how the experiment was performed and how they liked how the data was pre-recorded.
"…it was nice to discuss tough concepts with someone else."
Some students mentioned wanting more workshops to cover more topics and for them to be referred to more in the lectures.
Some still thought they were too long.

Did the workshop sessions of this course contributed significantly to your understanding of heat transfer concepts?
12/16 yes

Favorite WS?
All of the workshops were mentioned but overwhelmingly the radiation one.

Least Favorite?
Not many workshops were disliked but a few students mentioned the resistance workshop.
"It was done rather late in the semester when we had moved on to other topics, se it didn't feel relevant to the lecture at the time."

Did the hands-on nature of the workshops contribute significantly to your learning of heat transfer concepts?
13/16

Do you recommend that these workshop sessions be offered in future versions of this class?
14/16

Why do recommend or not recommend offering these workshops in the future?
"I think that as an augmentation to the lecture it really helps my understanding of the material. While I can't say my grades in this class were amazing, I do feel that I learned a lot, and I think that the workshops helped me in how I think about and approach problems."
"Actually feeling temperature gradients does more for me than looking at a graph."

Do you recommend that we extend this workshop format to other Mechanical Engineering courses?
13/16