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.

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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^{o}C
100W
77^{o}F
100W/m^{2}

Check all that apply, answer on Qualtrics

Q3: What is a typical heat flux measurement?

25W
25J
25W/m^{2}
25^{o}C

Answer on Qualtrics

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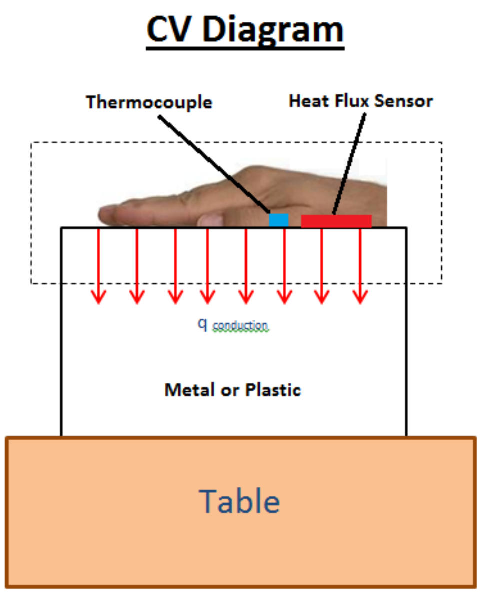
STEP 1: GENERATE IDEAS

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

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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.

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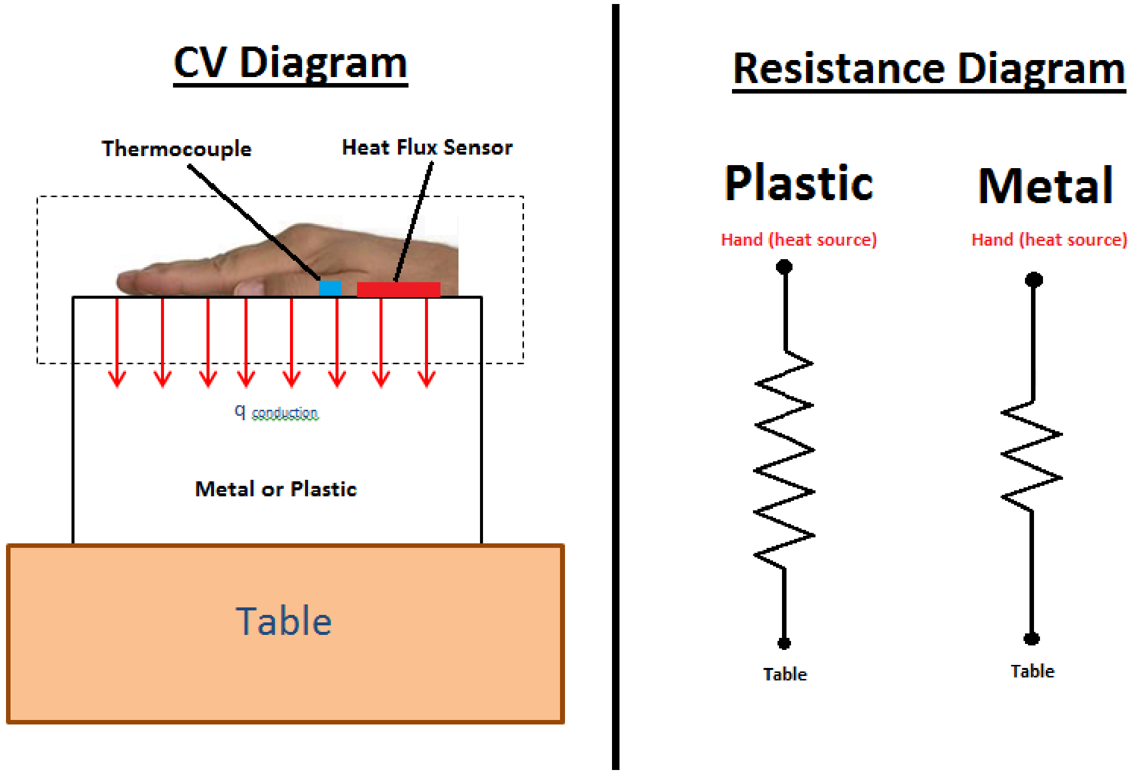
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

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

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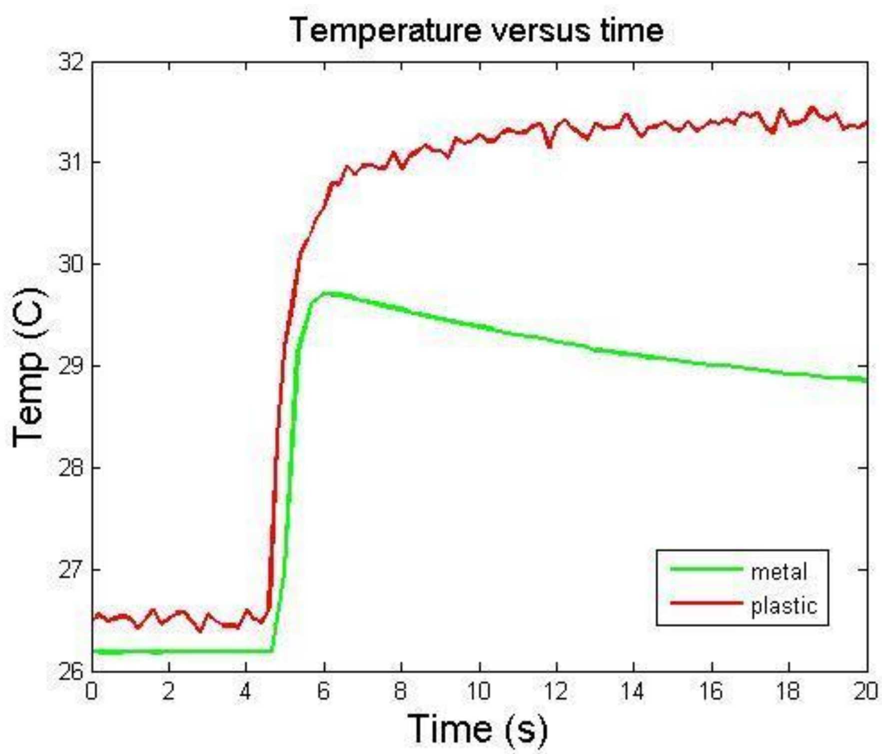
STEP 4: TEST YOUR METTLE



(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

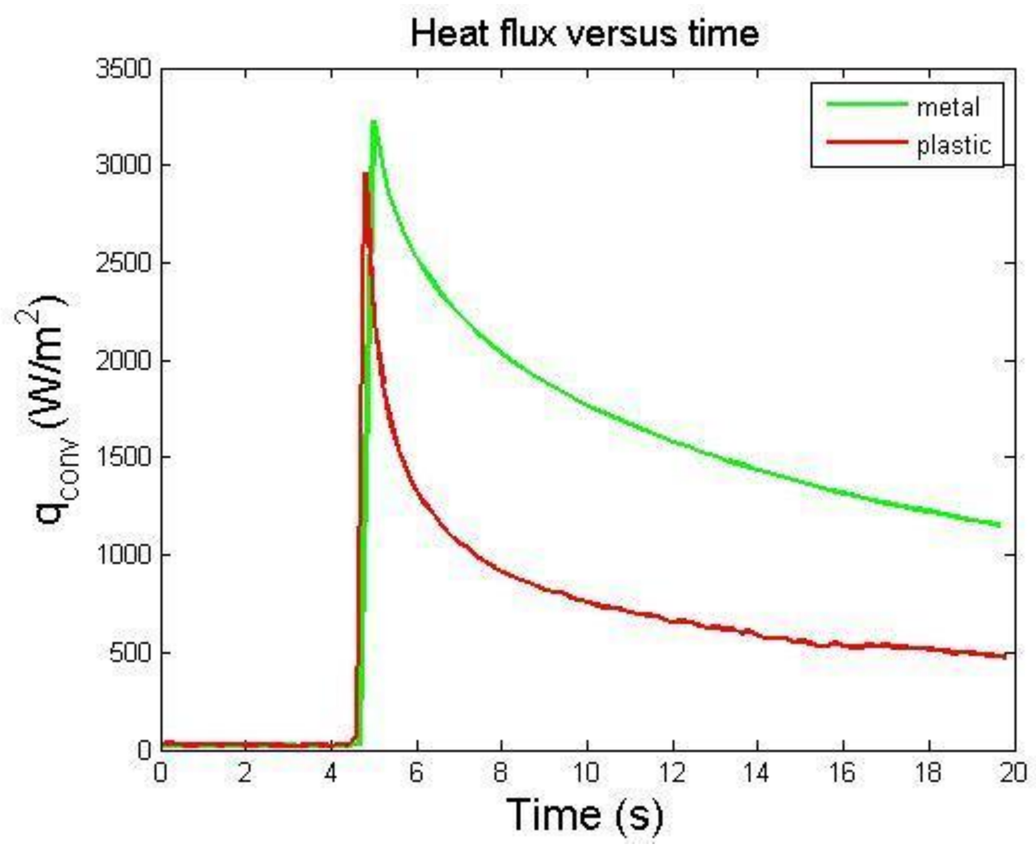
Part 3

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.

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

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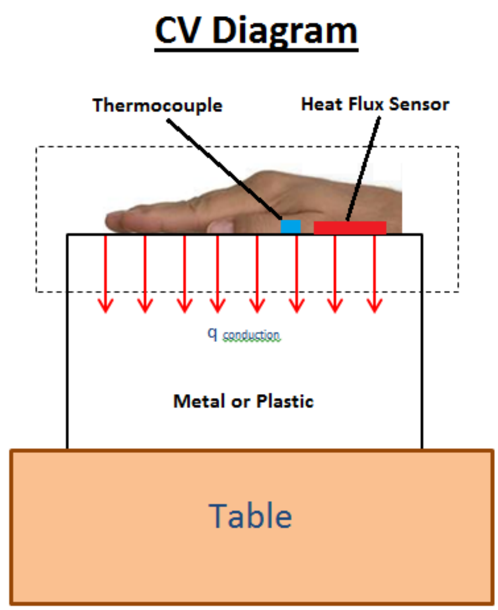
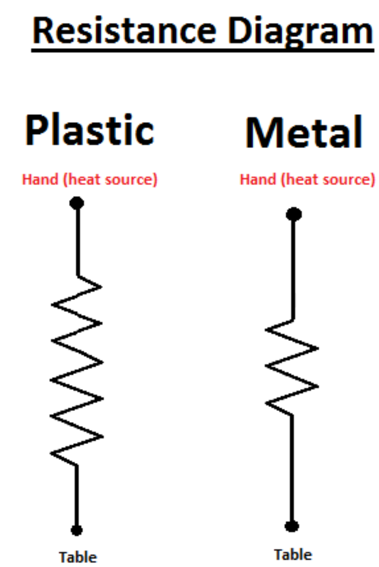
TEMPERATURE AND HEAT FLUX MEASUREMENTS IN CONDUCTION

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.

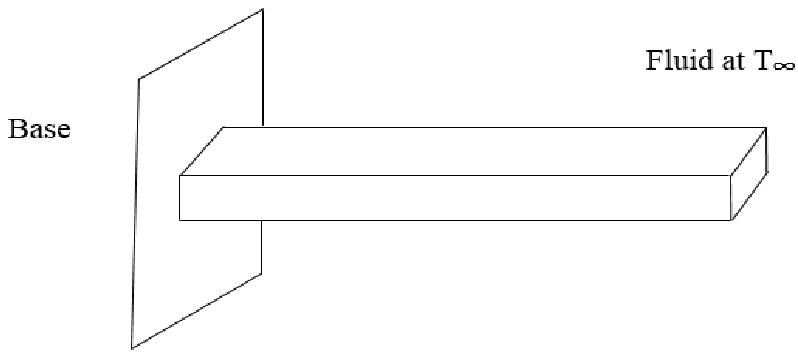
Use these tools to determine the convection coefficient and temperature distribution at three air speeds.

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.



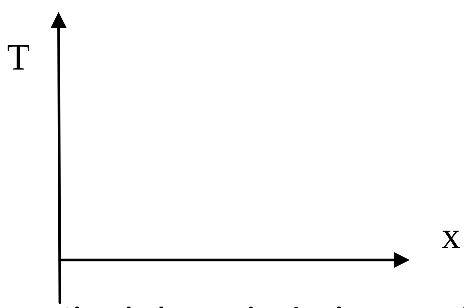
Next, frame your <u>**hypothesis**</u>: (write your answers in the spaces below).

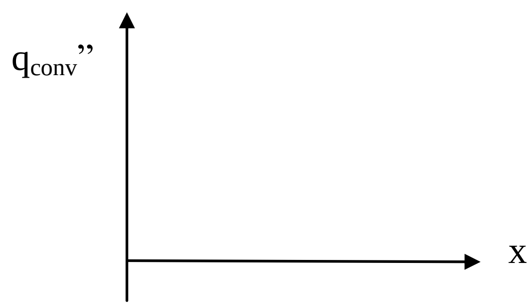
1. **How will the convection coefficient change as the air speed is increased?**

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 <u>convective</u> heat flux distribution along the fin length.**





5. **Sketch the <u>conductive</u> heat transfer distribution along the fin length.**

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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

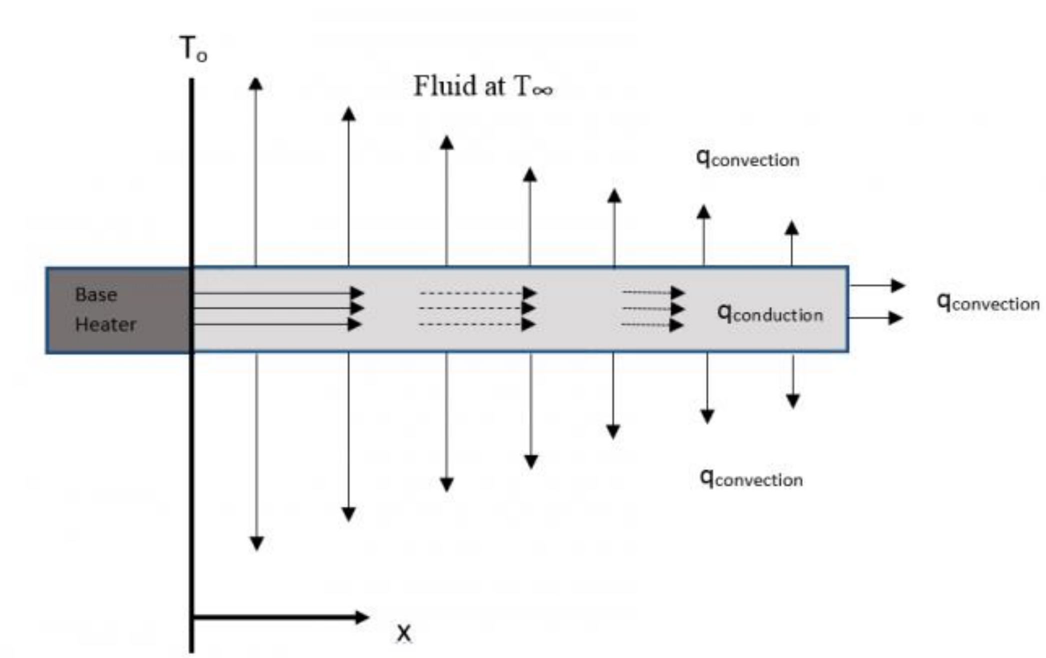
For heat convection, the rate equation is known as Newton's Law of Cooling. The rate equation is expressed as:

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

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.

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

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

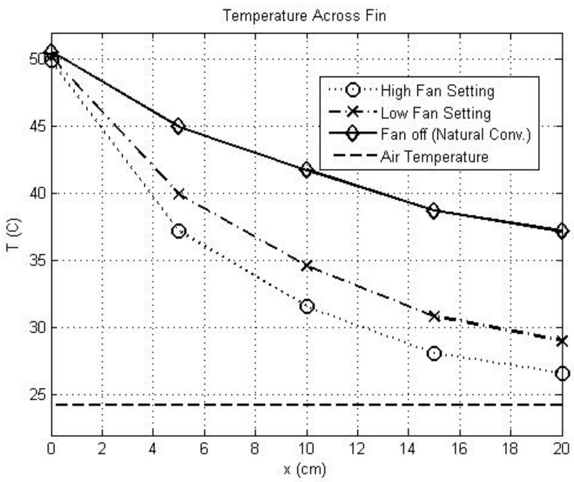
The following video shows you the experimental setup and procedure required for temperature and heat flux measurements of the fin.The locations of the six thermocouples are fixed.

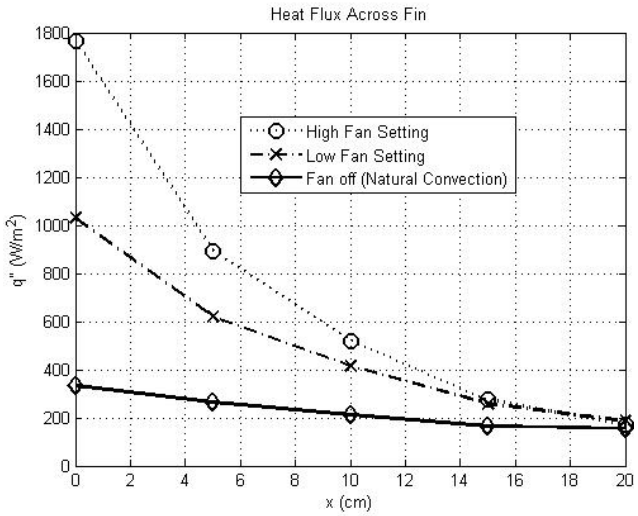
Video 6: "Workshop 2"

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. ESTIMATE 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 (^{o}C)	h $(\frac{W}{m^2K})$	q" $(\frac{W}{m^2})$	T_f (^{o}C)	h $(\frac{W}{m^2K})$	q" $(\frac{W}{m^2})$	T_f (^{o}C)	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?

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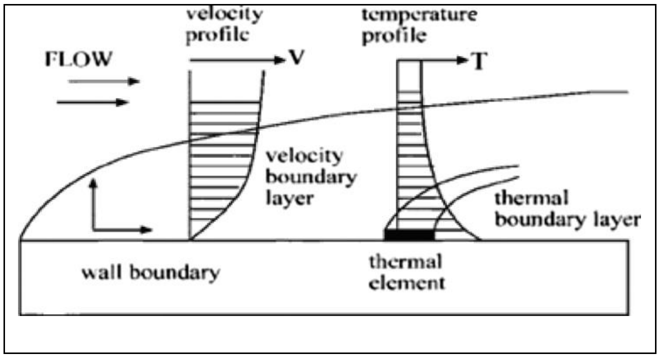
STEP 2:GATHERING PERSPECTIVES AND RESOURCES
STEP 3: RESEARCH AND REVISE

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.

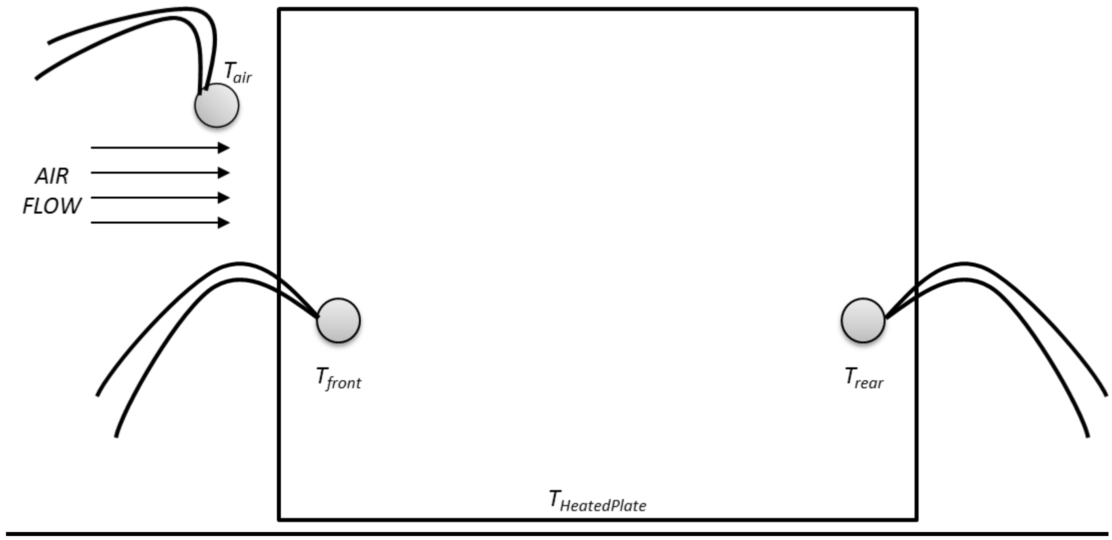
$R'' = 1 / h_x$

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

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.

<u>EXPERIMENTAL SESSION</u>

- 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 (^{o}C)	**Back Temp (^{o}C)**	**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:

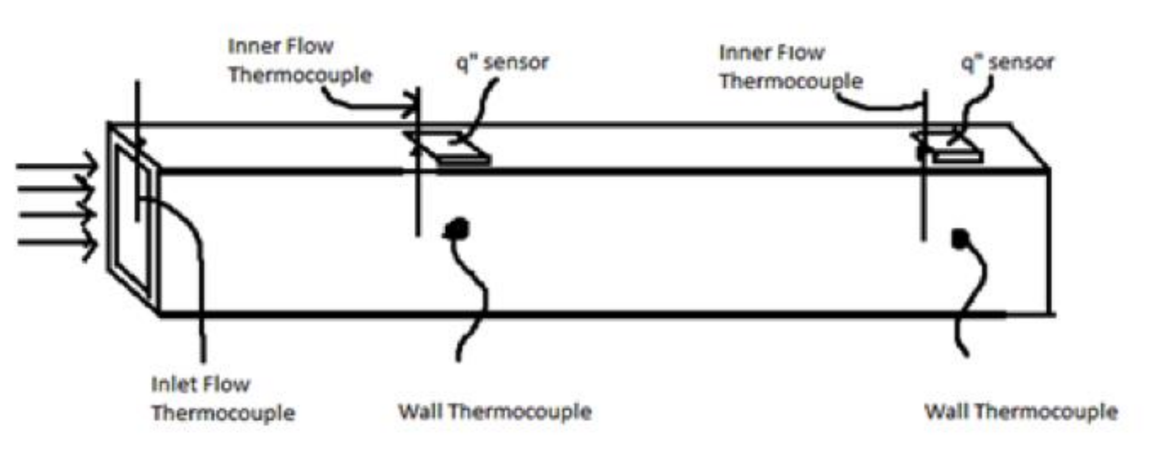
Your manager has an idea to cool a stream of gas using some aluminum square channels that are available. He wants you to size the system and evaluate its thermal performance. The channels are one-inch square outside dimensions, with a 1/16 inch wall thickness. Your challenge is to determine the mass 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

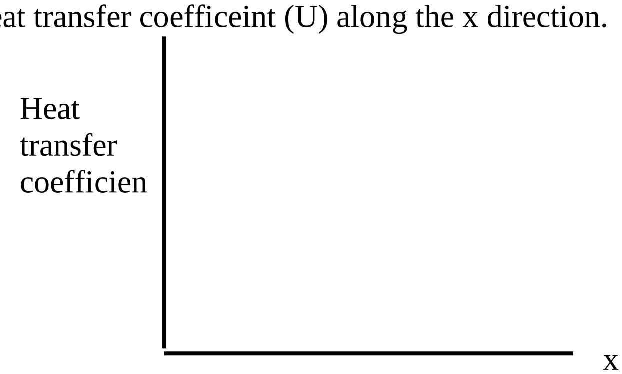
The goal of this phase is to establish a hypothesis for the channel operation.
As a team, discuss the following questions

- 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

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

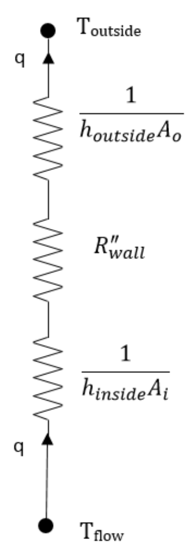
where $\dot{m}$ is the mass flow rate of the fluid and P is the perimeter of the channel. In terms of a uniform temperature heat sink $T_{outside}$, the temperature distribution is

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

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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ME 3304: HEAT & MASS TRANSFER

CHALLENGE-BASED WORKSHOP #4:
INTERNAL FLOW

STEP 2: GATHERING PERSPECTIVES AND RESOURCES

STEP 3: RESEARCH AND REVISE

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/m^2)	T_{flow} (°C)	T_{wall} (°C)	h_{inside} (W/m^{2}K)	$h_{outside}$ (W/m^{2}K)	U_o (W/m^{2}K)
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

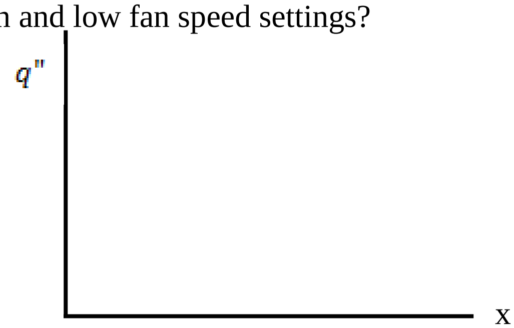
CHALLENGE-BASED WORKSHOP #4:
INTERNAL FLOW

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.

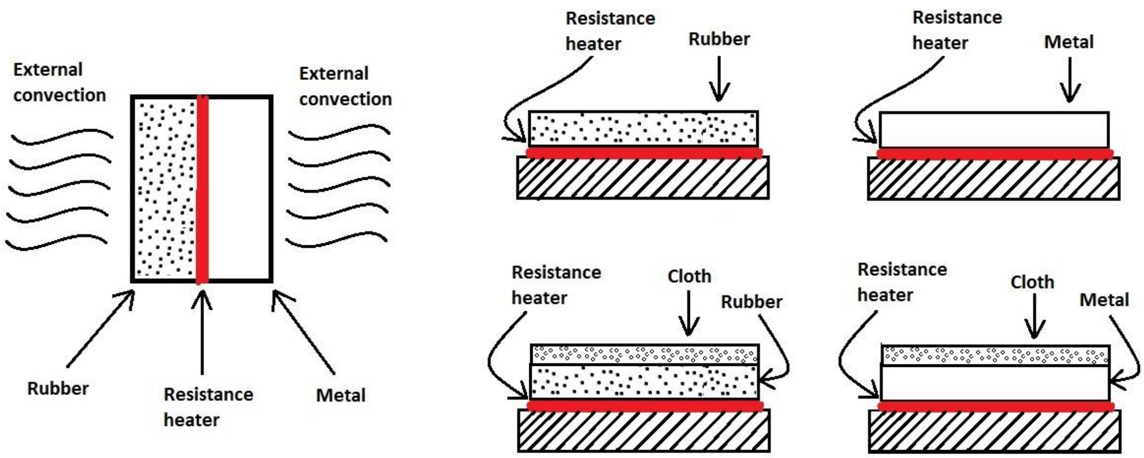
Context and Challenge:

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}:				

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.

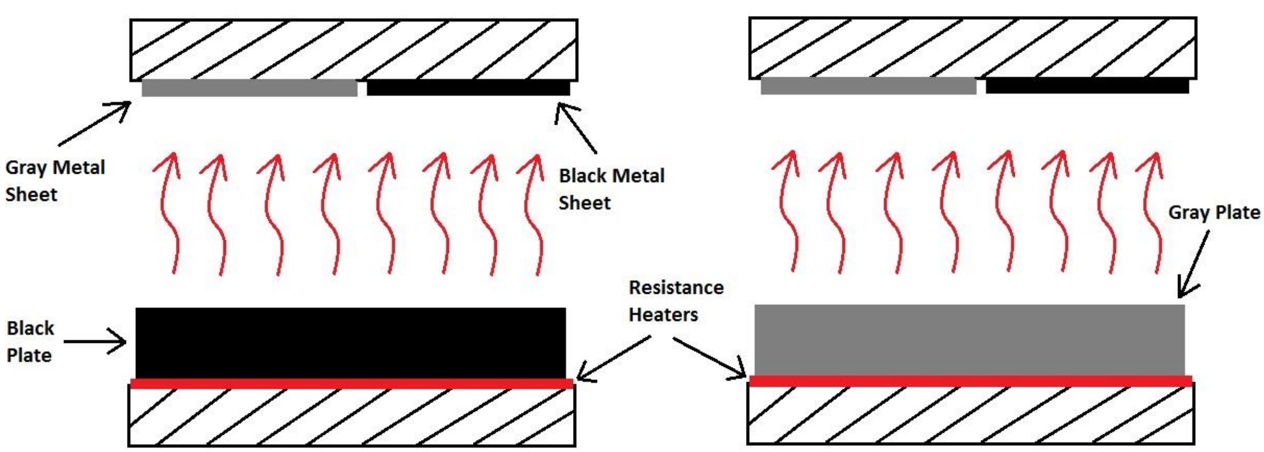
Challenge Question:

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 **<u>hypothesis:</u>**

- 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

$$E_b = \sigma T^4 \quad (1)$$

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

$$E = \varepsilon E_b = \varepsilon \sigma T^4 \quad (2)$$

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

$$G_{absorbed} = \alpha G \quad (3)$$

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

$$\alpha = \varepsilon \quad (4)$$

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.

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

(5)

where the radiosity is defined as

$$J = \varepsilon E_b + \rho G \quad (6)$$

When the two surfaces are black, the resulting radiation exchange between them is

$$\frac{q_{12}}{A_2} = F_{21}(E_{b1} - E_{b2}) \quad (7)$$

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?

Default Question Block

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

Follow along and answer the questions on the provided worksheet before moving on.

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

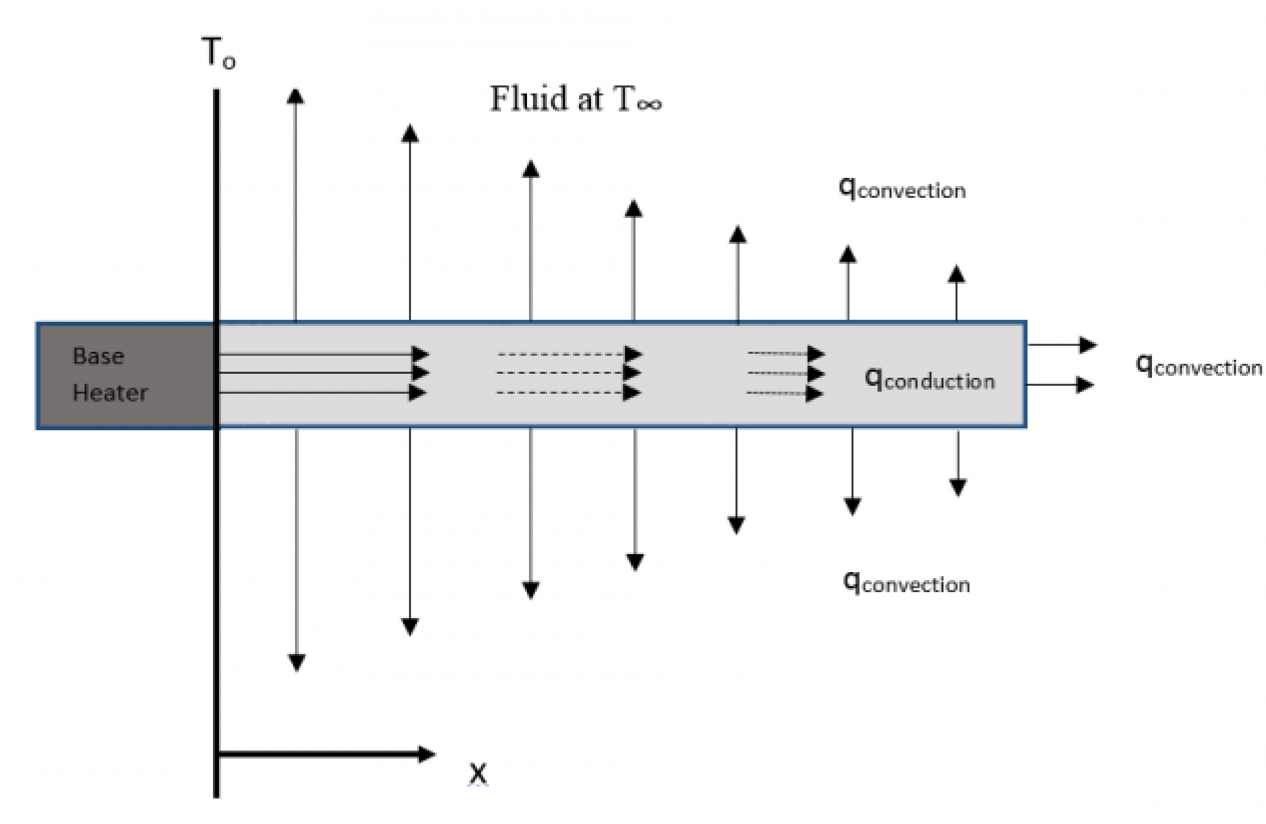
For heat convection, the rate equation is known as Newton's Law of Cooling. The rate equation is expressed as:

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

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.

<u>**EXPERIMENTAL SESSION:**</u>
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.

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

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

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.

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.