Heat Transfer Workshop 1 Introduction to Heat Flux Sensors

Name ___________________

This series of workshops is designed to help you understand heat transfer and temperature. Temperature is what most people measure, but heat transfer is equally important for engineering applications. The workshops use a combination of thermocouples and heat flux sensors to measure both of these quantities simultaneously. The sensor output is read by a data acquisition board (DAQ) that is connected through a USB port to a laptop computer. A program is loaded on the computer to graphically display results and provide a control panel.

Heat transfer (q) is the movement of thermal energy as a function of time. Typical units are watts, the same as power, which is the movement of mechanical energy as a function time. Heat flux is heat transfer per surface area (q''), with units of watts per square meter. This is analogous to a power density. It is measured across a thin, flat sensor that is encapsulated in a plastic cover. It outputs a voltage (E), which is directly proportional to the heat flux according to a supplied calibration (S), typically given as microvolts per watt per square meter, $q'' = E/S$. The computer program automatically does this conversion when supplied with the sensor's calibration value.

To measure temperature two thermocouples are provided. One is attached as part of the heat flux sensor. The other is a separate set of wires, welded together at one end to form the thermocouple junction. Thermocouples measure the difference in temperature from this junction to the connection point of the other end of the wires. The DAQ automatically measures the connection temperature and adjusts the voltage output to give absolute temperature values.

Together, this allows direct measurement of both individual temperatures and temperature difference. Heat transfer is driven by temperature difference. There is always a source of thermal energy at a higher temperature that moves to an energy sink at a lower temperature. Consequently, it is important to know the source and sink temperatures and the resulting heat flux in an engineering system.

The heat flux sensor kit provides the components as shown in Fig. 1. Included is a heat flux sensor with a thermocouple, a second separate thermocouple, a DAQ, an aluminum coupon, an aluminum fin, a small piece of wood, a thin heater and a small piece of cloth. The heater is designed to take power from the DAQ to provide a source of heat for some of the workshops. Many of the workshops use the human body as a heat source, which allows you to feel the thermal process while measuring the results.

Fig. 1 Heat Flux Sensor Kit Components

To make the measurements put the heat flux sensor between a heat source and a heat sink. This can be as simple as a desk and your hand or your arm and the surrounding air. The heat flux sensor can be taped to a surface or placed between two objects to hold it in place. Single-sided can be used over top of the sensor or double-sided tape can be used between the sensor and a surface. In either case the goal is to create good contact between the entire sensor and the surface to obtain a good reading.

Heat Transfer Workshop 1 Introduction Assignment

Name ________________________

1. Watch the introductory video on Heat and Temperature. https://youtu.be/1SX8u3qXo0A
2. Assemble your system. Make sure the wiring is correct as shown in Fig. 2. The placement of the colored wires is important. Starting from the left, the first two wires are the heat flux sensor (**Channel #1**(+) is white then **Channel #1**(-) is bright red). The next two wires are the thermocouple **(Channel #2**(+) is blue then **Channel #2**(-) is dark red). The next two are for the second thermocouple (**Channel #4**(+) is blue then **Channel #4**(-) is dark red).
3. Make sure the proper computer programs are installed on your computer.
4. Plug in the DAQ to a USB port (at least 2.0 or higher).
5. Start the program. A screen should appear as shown in Fig. 3.
6. Toggle the switches on the screen to make sure that the data acquisition is working. The plots should move in real-time if it is working.
7. Record the heat flux and sensor temperature from a source to a sink. Note that the output from the heat flux sensor is directional. In one direction the heat flux should read positive and if the sensor is flipped over the output should be negative. The thermocouple, however, only measures a temperature at a location. It does not have positive and negative values. In all cases, if a wire is broken or disconnected, the output will be very large and unresponsive. Use the save button to create an excel file. This file will have four columns beginning with time in seconds, followed by the heat flux in W/m^2, the third column is the sensor temperature (°C), and the fourth is the second temperature (°C).

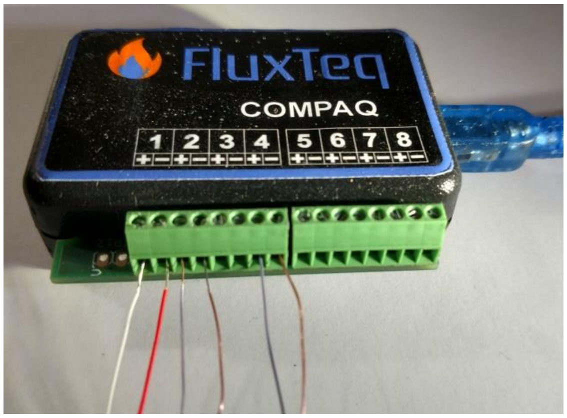
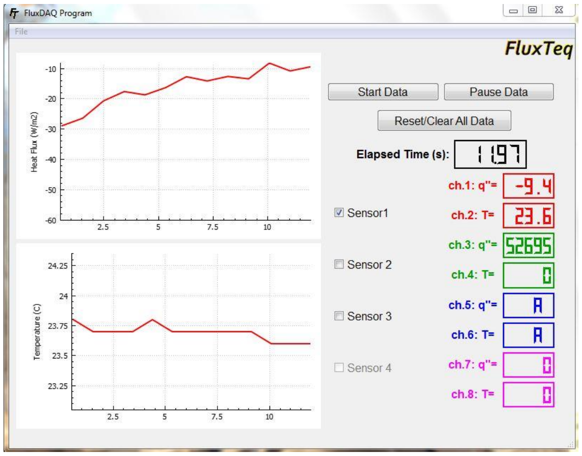


Fig. 2 Picture of DAQ wiring.



Elapsed Time (s): 11.97

☑ Sensor1
☐ Sensor 2
☐ Sensor 3
☐ Sensor 4

ch.1: q"= -9.4
ch.2: T= 23.6
ch.3: q"= 52695
ch.4: T= 0
ch.5: q"= A
ch.6: T= A
ch.7: q"= 0
ch.8: T= 0

Fig. 3 Computer operating screen.

<u>Measurement Description:</u>

q" = ________________ T = ________________

Are these values what you expected (including sign and direction)?

Explain why.

Heat Transfer Workshop 2 Body Metabolism Introduction

Assignment: Watch the introductory videos on Heat and Temperature

The human body is a sophisticated chemical reactor using metabolism for all of its activities. The energy that it produces and uses must eventually leave the body and go into the environment either as heat or work. The net work that is produced is usually small in comparison to the total energy produced. Therefore, one direct measure of the "calories burned" is the net heat transfer from the body to the environment.

Your challenge in this workshop is to estimate the calories that you burn in a day by measuring the heat transfer from your body with your heat flux sensor system. The human body has a typical surface area of 1.5 to 2.5 m^2, depending on the person's size. A common equation to estimate surface area is

$$A_s = \sqrt{\frac{\boldsymbol{H\,m}}{\boldsymbol{C_1}}} \qquad \text{where } C_1 = 36 \text{ kg/m}$$

This gives the area A_s in units of m^2 when the height H is in meters and body weight m is in kilograms.

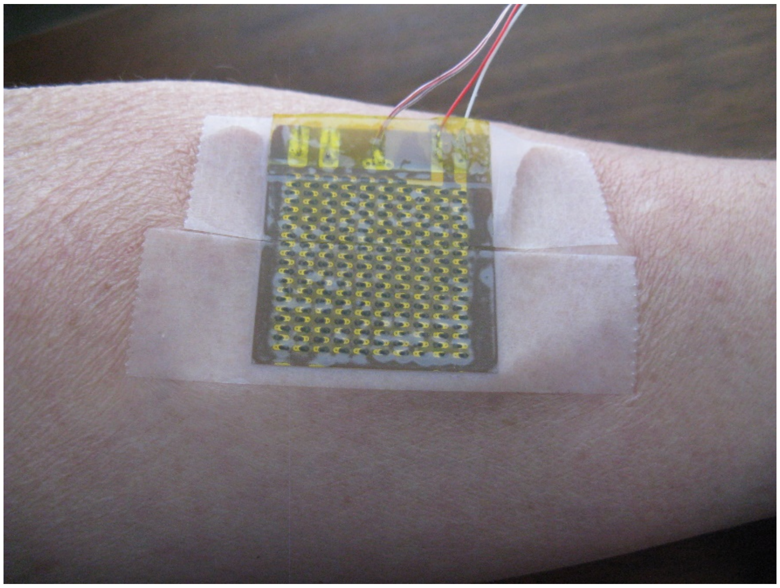
To make the measurements simply tape the heat flux sensor to different parts of your body on both exposed skin and underneath clothing. Single-sided tape can be used over top of the sensor or double-sided tape can be used between the sensor and the skin. In either case the goal is to create good contact between the entire sensor surface and the skin to give a good pathway for the heat transfer through the sensor, as illustrated in the figure. The heat flux should read positive if the leads are facing out. Check that you are measuring positive heat flux. If not, flip the sensor over.

Show the values on the worksheet and indicate where they were taken. Then average the temperature and heat flux values and use your estimated body area to find the total heat lost in both watts and calories per day. Show all of your work and equations used.

Note: One calorie is the equivalent of about 4.2 kJ.

1 inch = 0.0254 m.

1 pound = 0.454 kg



Heat Transfer Workshop 2 Body Metabolism Results

Name ________________________

Your challenge is to estimate the calories that you burn in a day by measuring the heat transfer from your body with your heat flux sensor system. Tape the heat flux sensor to different parts of your body on both exposed skin and underneath clothing. Show the values below and indicate where they were taken. Then average the temperatures and heat flux and use your estimated body area to find the total heat lost in both watts and calories per day. <u>Show all of your work and equations used.</u>

	Location	**Exposed/Unexposed**	**Surface Temp. (ºC)**	**q'' (W/m^2)**
1.				
2.				
3.				
4.				
Average				

Estimated body surface area, A_s =
H =
m =

Total q =

Calories per day =

How does this value compare with your usual caloric intake?

Why is there a discrepancy if any?

Why is the heat flux higher when the skin is exposed (not covered)?

Why is the surface temperature lower when the skin is exposed (not covered)?

Heat Transfer Workshop 3 Introduction to Fins

Assignment: Look at the definition of fin efficiency and how that relates to the temperature distribution in a fin. Compare measured and theoretical values.

In this workshop you use the thin piece of aluminum as a fin that is powered with the thin-film heater supplied with the kit. The heat flux gage can be used to measure the total heat transfer supplied to the fin. The fin efficiency has a simple definition of this actual heat transfer relative to the maximum heat transfer that would occur if the entire fin was at the base temperature.

$$\eta_f = \frac{\boldsymbol{q_f}}{\boldsymbol{h\,A_f(T_{base} - T_\infty)}}$$

h is the heat transfer coefficient, A_f is the total surface area of the fin, q_f is the actual heat transfer from the fin. $A_f = 2\,w\,L + 2\,t$, where w = width, L = length from the base, and t = thickness.

Fig. 1 shows an example of a typical temperature distribution along the length of a fin. Fig. 2 is a picture of the aluminum fin supplied as mounted on the heater and heat flux sensor.

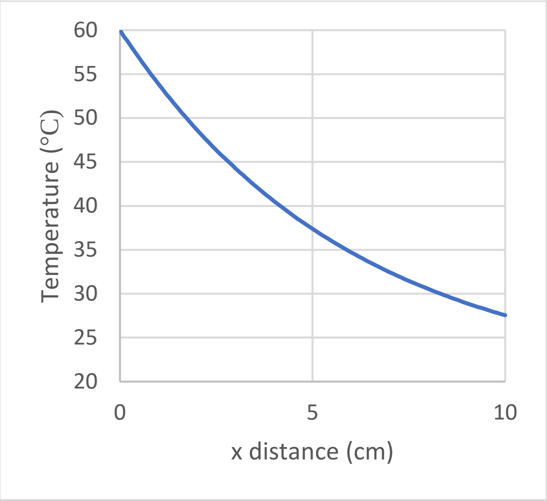


Fig. 1 Sample Fin Temperature Distribution

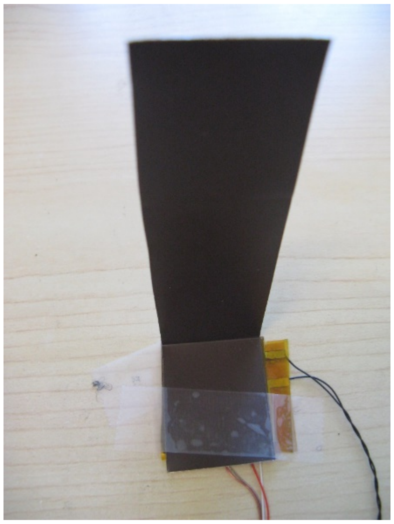


Fig. 2 Fin mounted on top of sensor and heater

The theory for a straight fin gives the fin efficiency as

$$\eta_f = \frac{\tanh(mL)}{mL} \quad where\;\; m_f = \sqrt{\frac{h\,(2w + 2t)}{k\,w\,t}}$$

in terms of the heat transfer coefficient, *h*, and the thermal conductivity of the fin, *k*. The hyperbolic tangent function (tanh) is a special exponential function. The values can be determined on some calculators or looked up online.

Heat Transfer Workshop 3 Fin Results

Name ________________________

Your challenge is to measure the heat transfer from the fin supplied and calculate the fin efficiency. Before starting, measure the size of the fin and record the dimensions. As shown in the figure, place the heater on any low conductivity surface followed by the heat flux gage and small end of the thin aluminum sheet. Use the small wood block to hold all of this in place. This arrangement will force most of the power from the heater through the heat flux sensor to the high conductivity aluminum sheet to then dissipate to the air. Turn on the heater and data acquisition system. Allow the system to come to equilibrium, which may take five to ten minutes. This will be clear when the temperature and heat flux measured by the sensor become nearly constant. Record these values. Make sure the second thermocouple is away from the fin out in the room.

The size of the heater is 1 inch by 1.2 inch, which gives a surface area of $A_h = 7.75\ \text{cm}^2$. Use this area with the measured heat flux to find the total input heat transfer that the fin dissipates to the air, $q = q'' A_f$. The fin is aluminum, which has a thermal conductivity of k = 175 W/m-K. The exposed surface of the fin will be twice the length times the width (neglecting the very thin edges). Because the effects of radiation can be approximately included in the heat transfer coefficient, treat the problem as shown in the introduction as being purely convection from the fin and conduction in the fin. Initially, assume the overall heat transfer coefficient from the fin to the air is $h = 15\ \text{W/m}^2\text{-K}$.

1. Measured Values:

Heat Flux, q'' = _____________

Sensor Temperature, T_s = ___________

Air Temperature, T_∞ = _______

Fin heat transfer, q = ________

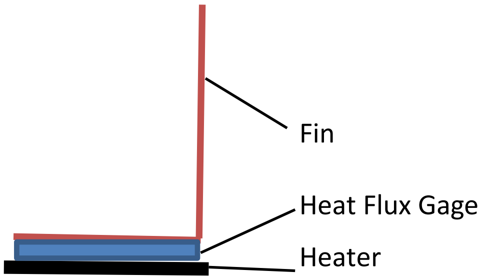
Fin width, w = _______

Fin length, L = _______

Fin thickness, t = 0.32 mm

Fin area, A_f = _______________

Fin efficiency, η_f = __________



2. Compare the measured results with theory using the equations given for a straight fin:

m_f = _________

$m_f L$ = ________

η_f = _________

3. How do these values compare with what was measured?

4. What would be a more appropriate value of heat transfer coefficient to make the theory and measurements match better?

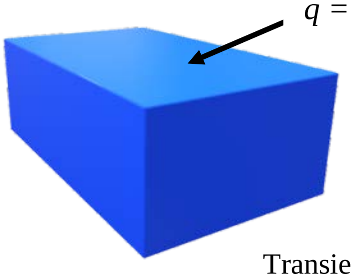
5. Feel the temperature distribution along the fin with your fingers. Does it match what you would expect?

Heat Transfer Workshop 4 Introduction to Transient Lumped Capacitance

Name ________________________

A simple model for systems with transient temperatures is the lumped capacitance method of analysis. This often works well for solid materials with high thermal conductivity. One often thinks of putting a piece of metal into a fluid at a different temperature which creates a step change in heat flux. However, it doesn't have to be a fluid. For example, your hands are often well perfused and make a good heat source.

Study the Lumped Capacitance Method in your heat transfer textbook. Draw the system and apply a transient energy balance for the piece of aluminum. The important assumption is that the temperature in the material is uniform in space, while it changes in time. Show the resulting algebraic solutions for the heat flux and temperature as a function of time, starting when the thermal event begins at time t_o with the initial temperature of the aluminum being T_i.



$q = U\,(T_h - T)$

Transient Energy Balance:

$$mC\,\frac{dT}{dt} = q$$

Write out the symbolic solution:

The aluminum temperature as a function of time, T =

The surface heat flux to the aluminum as a function of time, q" = U (T_h – T) =

The exponential time constant for this process, τ =

Heat Transfer Workshop 4 Results

Name _________________________

Use the piece of aluminum in your kit by putting the heat flux sensor on one side and then wrapping the cloth provided (in the kit) around it to provide some thermal resistance. First use the DAQ with the free thermocouple between your hands to record the steady temperature of your hands, T_h __________. Then restart the data acquisition and place the aluminum piece with the heat flux sensor and cloth between your hands. Record the temperature and heat flux of the sensor at the surface of the metal for about one minute. Save the file. Based on the measured heat flux and temperature difference, assuming your hands stay at the same constant temperature previously measured, calculate an overall heat transfer coefficient at each time. Plot the values as a function of time and take the average, U = _________________

The mass of the aluminum block is about 14 grams and the dimensions are 2 in. by 1.25 in. by 1/8 in. think. Calculate the corresponding surface area of the sides in contact with your hand,
Surface Area, A_s = ___________

Use these values with the properties of aluminum (C = 900 J/kg-K) and the average heat transfer coefficient U to calculate the value of the time constant, τ = _________________.

Then use this time constant and the theoretical solutions of the lumped capacitance model from the previous page to predict the temperature and heat flux. Plot these predicted values along with the measured curves and compare. Attach your three plots (Temperature predicted and measured, heat flux predicted and measured, and transfer coefficient, U).

1. How much variation of the overall transfer coefficient was found over time?

2. Why is the value of U not actually constant?

3. How well does the predicted temperature curve based on the calculated time constant and initial temperature difference match the measured curve?

4. How well does the predicted heat flux curve based on the time constant, average heat transfer coefficient and initial temperature difference match the experimental values?

5. How did the metal piece **feel** as a function of time during the test?

Heat Transfer Workshop 5 Transient Thermal Resistance Introduction

Name ___________________________

One very useful model of transient heat transfer is the semi-infinite solid. This combines the effects of the thermal resistance of the material along with the thermal capacitance of the material to absorb thermal energy. The main assumptions are that the material is thick (semi-infinite) and that heat transfer is one-dimensional. Look in a heat transfer text to find the theory of semi-infinite heat transfer. Although the mathematics involves partial differential equation solutions, the results are rather simple. If a constant temperature source T_s is applied to the surface of the material without any contact resistance, the resulting heat flux into the surface is

$$q'' = \frac{\sqrt{k\rho C}}{\sqrt{\pi t}}(T_s - T_i)$$

The initial temperature of the material is a uniform T_i and the surface temperature change happens at time $t = 0$. The properties of the material are thermal conductivity k, specific heat C, and density ρ.

The required thickness is a function of time. Conduction heat transfer is a diffusion process that propagates into the material as time increases. Consequently, the thickness to appear to be infinitely thick increases with time. A good approximation for this thickness L is

$$L = 2\sqrt{\alpha t}$$

where the thermal diffusivity $\alpha = k/\rho C$. It is an important property for transient heat transfer problems that indicates how fast heat transfers into a material.

Here are properties of concrete and carpet that will be used in this workshop. Calculate the remaining values of thermal diffusivity and penetration depth for the semi-infinite solution:

<u>Concrete</u> $L = 2\sqrt{\alpha t} =$

ρ = 2,300 kg/m^3; C = 880 J/kg-K; k = 1.4 W/m-K

α =

<u>Carpet</u> $L = 2\sqrt{\alpha t} =$

ρ = 800 kg/m^3; C = 1,200 J/kg-K, k = 0.05 W/m-K

α =

Another way to view this problem is in terms of the thermal resistance of the material R''. It is defined as the ratio of the temperature difference to the heat flux.

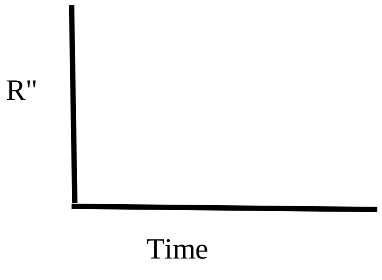
$$R'' = \frac{(T_s - T_i)}{q''}$$

Determine the theoretical value of thermal resistance for the constant surface temperature semi-infinite solution,

$R'' =$

How does it vary with time?

Sketch how it should vary.



Heat Transfer Workshop 5 Transient Resistance Results

Name __________________________

The goal of this workshop is to look at the heat transfer response of two materials with very different properties – concrete floor and carpet. Use your hand as a heat source and the heat flux sensor to measure the surface heat flux and surface temperature as a function of time. The goal is to see how the properties of these different materials affect your results.

a) Put the sensor on a concrete floor, start the data acquisition and then firmly place your hand entirely over the sensor for about 20 seconds.

b) Now put the sensor directly onto a carpet and repeat.

From your saved data files, plot the temperature as a function of time for both materials on the same graph and compare. Do the same for the heat flux on a second graph. Model the solid material as a semi-infinite solid assuming that the sensor temperature is the surface temperature T_s. For the initial temperature of the material T_i use the sensor temperature before you apply your hand to create the thermal event. Use the measured heat flux with these measured temperatures to calculate the apparent thermal resistance in each material as a function of time, $R'' = (T_s - T_i)/q''$. Plot R'' for the concrete and the carpet on the same graph for the time period where your hand is on the sensor. Attach the three plots (temperature, heat flux and thermal resistance) to hand in.

1. Based on your calculations for the thermal penetration depth *L* are the materials you tested sufficiently thick to assume they are “semi-infinite”? Why?

2. Is the graph of your results for thermal resistance R'' similar in shape to the theory shown in the introduction to Workshop 5?

3. Physically (apart from the equations) why does the thermal resistance change with time?

4. How does the value of thermal resistance vary between the two materials? Why? (look at thermal conductivity values)

5. Which material has the higher heat flux? Why?

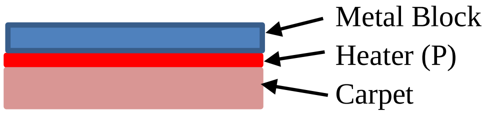
6. Which material has the larger change in temperature? Why?

7. Even though the initial temperature of the carpet and the concrete are nearly the same, why does concrete feel colder than the carpet (insulation)?

Workshop 6 Introduction to Heat Sinks and Energy Balances

Name __________________________ **Review Energy Balances**

This workshop uses the heater to emphasize thermal resistance and the energy balance. Specifically, where does the thermal energy from the heater go and how does it get there? This is an important problem in many thermal systems. To make it simple, it will be assumed to be one-dimensional. On one side of the heater will be a low conductivity material and on the other will be a high conductivity material, both starting at the same temperature. When the heater is turned on, heat flux will go to each of the materials. The heat flux sensor can be used to measure how much goes to each material.



The energy balance can be used to show that the total power from the heater P has to go to the combination of the two materials. Draw the overall energy balance on the figure and write the algebraic energy balance here in terms of the heat transfer to the metal q_m and the carpet q_c.

The relative thermal resistances will dictate the relative size of q_m and q_c (how much energy goes to each material). Because there is only one heat flux sensor, you will need to use it twice. First to measure what goes to the metal and then what goes to the carpet.

Workshop 6 Results

Name _______________________________

1. Place the heater on a piece of carpet or other good thermal insulator and place the metal piece over top. Slide the heat flux sensor between the metal and the heater. Start the data acquisition to establish the steady-state condition then turn on the heater. Allow the heater to run for about one minute to clearly see the response of the temperature and heat flux. Next move the heat flux sensor between the heater and the carpet. Repeat the data acquisition for this case. Plot the heat flux and temperature responses for both cases. Add these plots to the this workshop sheet.

2. Draw the system for each case and clearly label the four main components: carpet, heater, sensor, and metal. Label the direction of the heat fluxes in each case – from the heater to the metal piece and the carpet.

a) Sensor between heater and metal	b) Sensor between heater and carpet
Measured from heater to the metal, q''_m =	Measured from heater to the carpet, q''_c =

3. Why are the heat fluxes so different in value?

4. Which material provides the better heat sink?

5. Why is one heat flux positive and one heat flux negative with the same sensor?

6. What is the total power flux provided by the heater? P/A =

.

7. What is the fraction of the power that goes to the metal, q''_m / (P/A) =

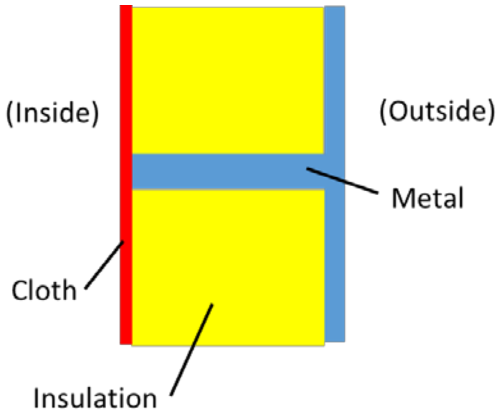
8. What is the temperature response for the two cases?

9. Why is the temperature response for the two cases so different than the heat flux?

Heat Transfer Workshop 7 Thermal Resistance Introduction

Name ____________________

In metal buildings insulation is often installed between the metal studs and the outer metal sheathing of the building. Consequently, there are two parallel pathways for the heat transfer – through the insulation and through the high conductivity metal studs. A layer of cloth is sometimes installed over the studs and insulation as shown below.



Draw a thermal resistance network for the different heat transfer pathways for this situation. Clearly identify which pathways are in series and which are in parallel. Write an expression for the overall thermal resistance of the wall.

You are embroiled in an argument over the value of the cloth. One side is arguing that the presence of the cloth has negligible effect on the heat transfer through the wall because it is so thin relative to the insulation. Therefore. it has a negligible effect on the overall insulation of the building. But the other side says that a covering over the metal studs will have a substantial impact on the heat transfer. Is there a way to prove who is right and convince everyone? What is the truth in this situation? This is often the task for engineers to develop logical explanations.

Heat Transfer Workshop 7 Results

Name ____________________

You are tasked with making some simple measurements to prove or disprove this argument by inserting a piece of cloth over the metal and then the insulation (carpet). Use your hand as a heat source on the heat flux sensor like you did in Workshop 5. This time compare the results while also adding a piece of cloth. Take about 20 or 30 seconds of data for each of the four combinations:

a) sensor directly on the metal block.
b) cloth between the sensor and the metal piece.
c) sensor directly on the carpet.
d) cloth between the sensor and the carpet.

1. Plot the heat flux values for each case and compare the resulting curves all on one graph. Attach your graph.

Calculate the approximate ratios of heat flux with and without the cloth for the same time after application of your hand (average several values from 10 to 20 seconds after the peak to provide a good comparison):

Metal: $q''_{\text{with cloth}}/q''_{\text{without cloth}}$ = _________ Carpet: $q''_{\text{with cloth}}/q''_{\text{without cloth}}$ = __________

2. What is the change in thermal resistance by placing the cloth onto the carpet?
(measurement uncertainty is at least 5%)

3. What is the change in thermal resistance by placing the cloth onto the metal?

4. Why is there a difference between the effects of putting the same cloth on carpet versus metal?

5. What is the answer to the original dispute? Will adding the cloth make a difference for the building?
How does the cloth make a difference in what you feel?

6. The cloth could be representative of fouling in a heat exchanger. What does this tell you about when fouling will or will not be important in heat exchangers?

Heat Transfer Workshop 8 Convection Introduction

Name ________________________ **Read about fluid convection**

Convective heat transfer occurs whenever there is a fluid next to a surface with a temperature difference. Your wrist is a good example. There is air movement due to buoyancy even in a room with no apparent overall air motion. In reality there is always some air motion – if a door is opened, if a person moves, if a piece of electronics is activated. These all cause unsteady and seemingly random air motion and surface convection. Even though this heat flux may not be very large, it can still be measured with the heat flux sensors in the course kits.

The effect of fluid motion on convection is incorporated in a coefficient h that is used to correlate heat flux with the temperature difference between the surface T_s and the fluid T_{fluid} . For example

$$q" = h\left(T_s - T_{fluid}\right)$$

This convection heat transfer coefficient is non-dimensionalized in the Nusselt number by a characteristic length L_c and the thermal conductivity of the fluid k

$$Nu = \frac{hL_c}{k}$$

The characteristic length is the same as used in the Reynolds number

$$Re = \frac{VL_c}{\nu}$$

where the fluid velocity is V and the kinematic viscosity of the fluid is ν. Correlations for the Nusselt number are often given in terms of the Reynolds number of the flow. Because of such correlations, heat transfer measurements are sometimes used as a method to infer the fluid the velocity. This will be demonstrated in the current workshop.

Heat Transfer Workshop 8 Convection Results

Name ________________________

Your first challenge is to measure heat convection coefficients using the heat flux sensor system. Tape the heat flux sensor to the inside of your wrist to measure the surface temperature and heat flux. Keep the second thermocouple out in the room to record the air temperature. Take about 20 seconds of data under each of three conditions (it can all be recorded in the same file). First turn your wrist with the sensor facing up and not moving, then turn your wrist so the sensor is facing down not moving, then move your arm in a circle to give motion relative to the air. What is the maximum heat flux that you can achieve moving your arm?

Calculate the heat transfer coefficients and corresponding Nusselt numbers for each condition. Neglect the effects of radiation. Use the diameter of your wrist as the characteristic length, L_C = d = _____ for Re and Nu, assuming your arm is a cylinder. Neglect the effects of radiation. Record your average values for the three conditions in the table below and calculate the corresponding heat transfer coefficient and Nusselt number.

	Wrist Facing Up	Wrist Facing Down	Arm moving
T_{air} (°C)			
T_s (°C)			
q" (W/m^2)			
h (W/m^2-K)			
Nu = hL_c/k			

The heat transfer correlation for air flow over a cylinder at the stagnation point is

$$Nu = 0.95\sqrt{Re}$$

Use this correlation to estimate the maximum velocity you achieved moving your arm from your measured Nusselt number.

Air Properties:

Diagrams, Equations and Calculations:

1. Re =

2. What was your maximum Velocity, V =

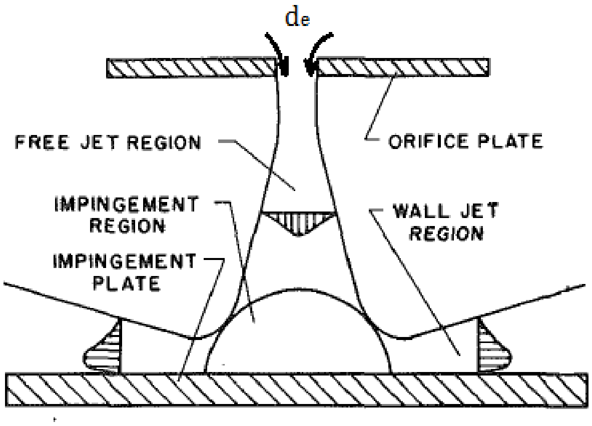
3. Which of the three orientations of the sensor on your wrist would you expect to give the highest heat flux? Why?

4. Which orientation would you expect to give the lowest heat flux?
Based on buoyancy, Why?

Heat Transfer Workshop 9 Introduction to Jets

Name ________________________

An air jet is a good means for providing convective heat transfer with a surface. This is why you blow on your food if it is too hot. A sketch of a typical an industrial jet is shown in the figure. Large arrays of hot air jets are often used in drying processes. Fans pressurize large plenums with many small orifice holes in a plate that then impinge on the opposing surface.



A common correlation for the heat transfer on the flat surface in the impingement region beneath an impinging jet is

$$Nu = 0.83\sqrt{Re}$$

where $Re = Vd/v$ and $Nu = hd/k$.

The thermal conductivity is k and the kinematic viscosity is v. The effective diameter of the jet at the exit is d and the velocity is V. The velocity can be determined from Bernoulli's equation. in terms of the plenum pressure p relative to atmospheric.

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

where ρ is the fluid density. Therefore, the pressure difference is

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

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Heat Transfer Workshop 9 Jet Results

Name ________________________

Your challenge today is to measure the convective heat transfer coefficient when you blow on something. Tape the heat flux sensor to your piece of aluminum and place it on a surface at room temperature. Put the wire connection side down next to the metal to get a positive heat flux. Tape the second thermocouple so that the bead is sitting above the sensor, but not touching it. This will provide a measure of the air temperature from your lungs. Start the data acquisition and blow as long and hard as you can. Then stop and save your data.

Note that this is a highly transient event and the direction of heat flux and temperatures may switch momentarily, giving what appears to be negative values of h. Use the plots of heat flux and temperature to interpret your heat transfer coefficients.

1. Give the maximum value of heat flux that you achieved.

Maximum q" =

2. Record the temperatures when the maximum heat flux occurs.

T_s =

T_{air} =

3. Calculate the corresponding heat transfer coefficient and Nusselt number. Look in a mirror to estimate the diameter of your mouth when you blow. Use this as the characteristic length, L_c = d = _____.

h = __________

Nu = hd/k = _________

4. From the Nusselt number correlation given in the Introduction, determine the corresponding velocity that this heat transfer measurement estimates, V = ____________

5. Your lungs can provide an air pressure of several inches of water. What lung pressure is required to provide the air velocity you calculated in 4? Assume that Bernoulli equation applies. (249 Pa = 1 in. H_2O)

Δp = _________ Is this value reasonable?

6. Show equations and calculations.

Air properties at 300 K
Thermal conductivity, k =
Density, ρ =
Kinematic viscosity, ν =

Heat Transfer Workshop 10 Window Conduction Introduction

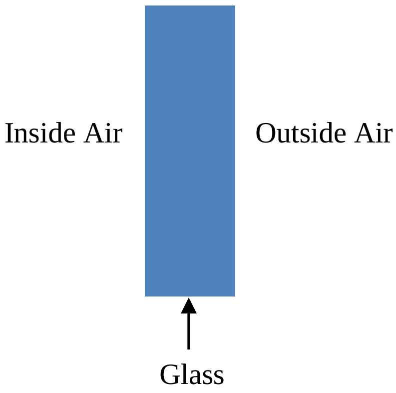
Name ______________________

Windows are a major source of heat loss in buildings. Many older windows and storm doors use a single pane of glass, typically 1/8 inch thick. This is still the case in the older engineering buildings on our campus. The thermal resistance of the window should be measurable from the heat flux q'' and temperature difference across the glass ΔT. At steady-state conditions the conduction heat flux is

$$q'' = \frac{k}{L}\left(T_{inside} - T_{outside}\right)$$

where k is the thermal conductivity of the glass and L is the thickness. The corresponding thermal resistance is

$$R'' = L/k$$



Note: It is very difficult to accurately measure the surface temperature of materials when heat transfer is occurring to or from the surface. Thermal contact resistance is relatively large, especially for the usual bead thermocouples. Conversely, the heat flux is typically measured over a much larger area and at steady-state conditions, what goes in must come out. Consequently, contrary to popular opinion it is normally much easier to accurately measure heat flux on a surface than temperature.

Heat Transfer Workshop 10 Window Conduction Results

Name __________________________

Mount the heat flux sensor on the inside of the window with the thermocouple on the side next to the glass. Measure the heat flux and temperature at steady-state. Then repeat for the outside of the window. Use the second thermocouple to record the air temperature at the same time. Record the steady-state values below and sketch the temperature distribution on the figure. Label the direction of the heat flux.

Draw and label the system with all measurements:

$T_{\text{glass inside}}$ =

$T_{\text{glass outside}}$ =

$T_{\text{air inside}}$ =

$T_{\text{air outside}}$ =

q''_{inside} =

q''_{outside} =

1. Why do the heat flux values have opposite sign between the inside and outside of the window?

2. Apply an energy balance around the window. What does it say about the relation between your measured heat flux values?

3. What reasons would cause the magnitude of heat flux measured values to not be equal?

4. Neglect radiation and solve the conduction equation for the temperature difference across the glass for the average heat flux. The thermal conductivity for glass is typically about $k = 1.0$ W/m-K and the thickness is about $L = 3$ mm.

Calculated ΔT = __________ Measured ΔT = ______________

5. Why are these values so different?

Heat Transfer Workshop 11 Introduction to Water Evaporation

Name _________________________ **Read about simultaneous heat and mass transfer**

The human body uses water evaporation as an important heat transfer mechanism. In addition, there are many industrial processes, especially for drying of products that use evaporation processes in air. Fortunately, convection mass transfer J can often be modeled in exactly the same way that convection heat transfer q_c is modeled. In terms of the transfer per area (flux)

$$q''_c = h\,(T_s - T_\infty)$$

$$J'' = h_m\,(C_s - C_\infty)$$

Heat flux is in terms of the temperature difference from the surface to the bulk fluid (air) and mass flux is in terms of the concentration difference of water vapor in air. These concentrations are equal to the density of water vapor ρ at the saturation temperature of water and can be found from steam tables. The relative humidity relates the actual water vapor concentration in air with this saturation value of water vapor all at the air temperature T_∞.

$$\varphi = {C}/{C_{sat}} = {C}/{\rho_\infty}$$

The heat transfer coefficient h and mass transfer coefficient h_m can be related for the same surface by the Lewis relation

$$h_m = h\,\frac{D}{k}\,Le^{1/3}$$

where D is the diffusion coefficient of water vapor in air and k is the thermal conductivity of air taken at the average temperature of the air $T_{av} = (T_s + T_\infty)/2$. The Lewis number Le is the ratio of the thermal diffusivity of air α to the kinematic viscosity v. For water vapor in air near room temperature conditions the Lewis number is nearly a constant value of 0.85.

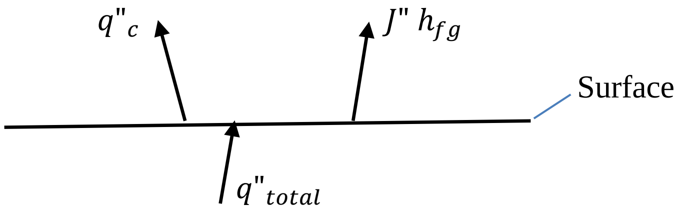
$$Le = {\alpha}/{D} = 0.85$$

This also provides an easy method to find the diffusion coefficient,

$$D = {\alpha}/{0.85}$$

The total energy flux from the surface is the combination of the convection mass transfer and the evaporation energy flux of the mass transfer. Because the water changes from liquid to vapor during evaporation, the enthalpy of vaporization h_{fg} must be included.

$$q''_{total} = q''_c + J''\,h_{fg}$$



Heat Transfer Workshop 11 Water Evaporation Results

Name ________________________

In Workshop 8 you measured convective heat transfer from your wrist. Now the challenge is to measure the combination of heat and mass transfer when sweat or water is introduced. First, tape the heat flux sensor to your wrist as before for the dry measurement. Keep the second thermocouple out in the room to record the air temperature. Take about 30 seconds of data (until steady) while moving your arm in air. Then place a wet cloth (included in your kit) that has been drenched with water over top of the sensor and repeat. The cloth dries out pretty fast so re-saturate the cloth each time before using it. Plot the heat flux as a function of time for both cases and note the change when the wet cloth is added.

Use the steady-state heat flux and temperature values to calculate the heat transfer coefficient when the arm is dry before the cloth is added. Neglect the effects of radiation. Assume the h you found stays the same (but not the surface temperature) when the cloth is added. Use this value with the Lewis Relation to calculate the corresponding mass transfer coefficient, h_m. Use the temperatures of the sensor and the surrounding air to find the corresponding saturation concentrations of water vapor. Assume a relative humidity to find the water vapor concentration in the air (start with 50%). Use these values to calculate the total heat flux for the wet case. Does it match? If not, adjust the relative humidity value that you use and repeat the calculations until you get a reasonable match with your data. Record your measured values below.

Measured Values	Arm Dry	Arm Wet
Total q" (W/m^2)		
T_∞ (°C)		
T_s (°C)		

<u>Calculated value of the heat transfer coefficient for the dry case</u>, h =

<u>Calculate values for the wet case using the Lewis relation:</u>

Air properties from tables at T_{av}: k = α = D =

Mass transfer coefficient, h_m =

Properties @T_s = , density of water vapor $\rho_s = C_s$ = enthalpy of vaporization, h_{fg} =

Guess φ =

Properties @T_∞ = . density of water vapor, ρ_∞ = $C_\infty = \varphi\ \rho_\infty$ =

Calculated mass flux, $J'' = h_m (C_s - C_\infty)$ =

Calculated evaporation energy flux, $J'' h_{fg} = h_m (C_s - C_\infty) h_{fg}$ =

Calculated convection heat flux when wet, $q''_c = h (T_s - T_\infty)$ =

Calculated wet total energy transfer, $q''_{total} = q''_c + J'' h_{fg}$ =

Fraction of energy transfer by mass transfer =

Equations and Calculations:

Heat Transfer Workshop 12 Introduction to Heat Transfer Coefficients

Name ____________________________ **Read about heat transfer coefficients**

A heat transfer coefficient is used to relate the heat flux between a surface and a fluid. For heat flux defined as positive from the surface

$$h = \frac{q''}{T_s - T_{fluid}}$$

where T_s is the surface temperature and T_{fluid} is the temperature of the bulk fluid. If the temperature difference is zero, the value of h is undefined. Therefore, heat transfer has to be provided into or out of the surface for h to have meaning. If there is no heat transfer occurring naturally, a heater may be added to provide a heat flux. The temptation might be to only use the heater and assume that all of the heat flux goes into the air by convection. This is generally not a good assumption. Without the heat flux sensor it is difficult to know how much of the thermal energy from the heater actually leaves to the fluid and how much is absorbed by the surface material. The value of a heat flux sensor is that it directly measures the heat flux from the heater on the surface of the wall to the fluid.

Placing a heater behind the heat flux sensor creates an artificial "hot spot" where the sensor is, however. This disruption of the surface temperature is known to increase the heat transfer coefficient at the location of the sensor. This results in measurement errors that can be quite large. The following reference gives additional details. There is also guidance on using heat flux sensors in the two ASTM standards that are listed.

Diller, T. E., "Heat Flux Measurement," Ch. 18, in Handbook of Measurement in Science and Engineering, Ed. M. Kutz, John Wiley & Sons, NY, 2013, pp. 629-659.

ASTM E2684-17, Standard Test Method for Measuring Heat Flux Using Surface-Mounted One-Dimensional Flat Gages. Ann. Book ASTM Standards, 15.03, 2017.

ASTM E2683-17, Standard Test Method for Measuring Heat Flux Using Flush-Mounted Insert Temperature-Gradient Gages. Ann. Book ASTM Standards, 15.03, 2017.

Heat Transfer Workshop 12 Results

Name ___________________________ **Read about heat transfer coefficients**

Normally the heat flux through building walls is very small. Consequently, to measure the convective heat transfer coefficient on the outside of the wall, add the heater provided in the sensor kit to give a measurable heat flux. Place it between the heat flux sensor and the wall of a building. Put the side of the sensor with the thermocouple away from the building to get a positive heat flux when the heater is operating. Turn on the data acquisition for at least 10 seconds and then activate the heater. Let it run for a least 30 seconds. Then find the average values before and after turning on the heater.

Outside Building	q'' (W/m^2)	T_s (C)	T_{air} (C)	h (W/m^2)
Before Heater				
After Heater				

1. Plot the temperatures, heat flux and heat transfer coefficient as a function of time. Attach to the workshop. Do the values of temperature and heat flux before the heater is turned on make sense?

2. Show the calculations for the heat transfer coefficients.

3. The heater increases the temperature of the sensor and the resulting convective heat flux, which makes it easier to determine the heat transfer coefficient. However, this increased surface temperature locally disrupts the thermal boundary layer, increasing the local heat transfer coefficient. Based on your measurements, how much does the h value increase for this case?

4. What happens to the heat transfer coefficient under transient conditions when the direction of the temperature difference changes from positive to negative?

5. What can you conclude about the limitations of heat transfer coefficients and how they are defined?

Heat Transfer Workshop 13 Radiation Introduction

Name ____________________ **Read about gray body Radiation**

The emissivity ε of a surface is a measure of the radiation heat flux or emissive power *E* that is emitted relative to the maximum from a "black body". This black body emissive power is defined from basic physics as

$$E_b = \sigma T^4$$

where the value of the constant $\sigma = 5.67 \times 10^{-8}$ W/m^2-K when the temperature is specified in Kelvin degrees. The emissivity is then simply

$$\varepsilon = {}^{E}/_{E_b}$$

When there are multiple surfaces exchanging radiation, all of the surfaces are both receiving and emitting energy. If the two surfaces are both black (ε = 1) and very near to each other, the radiation heat flux from surface 1 to surface 2 is simply

$$q"_{12} = E_{b1} - E_{b2} = \sigma\,(T_1^4 - T_2^4)$$

If one of the surfaces is gray (ε < 1), an additional thermal resistance needs to be included as

$$q"_{12} = \frac{E_{b1} - E_{b2}}{1 + \frac{1-\varepsilon_1}{\varepsilon_1}}$$

This reduces to

$$q"_{12} = \varepsilon_1 (E_{b1} - E_{b2})$$

Remember this is the radiation flux for two surfaces very close together with one surface black and one gray.

Heat Transfer Workshop 13 Radiation Results

Name ______________________ Read about gray body Radiation

You are asked to measure the emissivity of a metallic surface. To do this, you are provided with a heated plate that is painted black on one-half of the plate. The other half is polished metal. Note that the plate is at a uniform temperature because it is thick and has high thermal conductivity. It should be about 90°C to easily feel the radiation. Compare the heat transfer from the metal (gray) surface to that of the painted (black) surface ($\varepsilon = 1$) at the same conditions. Use the heat flux sensor to measure the radiation emission from the plate. Mount the sensor onto your small aluminum block to provide a heat sink. Use a piece of black (electrical) tape to give a nearly black surface ($\varepsilon = 1$) to the heat flux sensor.

1. Put your hand close to the plate first over one half and then the other to feel the difference between the black and gray surfaces. Note how it feels if you move farther away. **DO NOT TOUCH the plate. It is VERY hot.**

2. Without touching the plate, put your free thermocouple between the plate and heater to measure the plate temperature Hold your heat flux sensor close, but not touching the plate. Take about 20 seconds of data for each of the black and gray surfaces and save in one file. Record the temperatures of the plate and sensor and the measured heat flux from each half of the plate to the sensor below. Find the corresponding emissivity of the polished metal.

	T_p (K)	T_s (K)	q''_{black} (W/m^2)	q''_{gray} (W/m^2)
measured				

3. How does the gray surface feel different than the black surface at the same temperature? Why is this?

4. To simplify the system analysis neglect convection and assume that the surfaces are very close (view factor between the sensor and plate is unity). Based on the equations in the introduction for this case the ratio of the heat flux for the two cases should be directly proportional to the ratio of the emissivities of the surfaces. Because the sensor is assumed black ($\varepsilon = 1$), this should give the gray surface emissivity as equal to the ratio of the gray surface heat flux to the black surface heat flux.

Evaluate, ε_{gray} = ______________

5. Explain why the plate did not feel as hot as you moved your hand away from the hot surface. (How does the view factor change?)

6. Based on the measured temperatures, find the black body emissive powers of the two surfaces, $E_b = \sigma T^4$. From the equations in the Introduction, calculate the predicted sensor heat flux from the black surface to the sensor, $q''_{black.}$ Explain any differences between the calculated and measured values of heat flux.

	T_p (K)	T_s (K)	E_{bplate} (W/m^2)	$E_{bsensor}$ (W/m^2)	q''_{black} (W/m^2)
calculated					

Show calculations:

Heat Transfer Workshop 14 Creativity

Name ________________________

You’ve had a chance to use your heat flux sensor system for a number of measurements in the real world so far this semester. These were designed to help you discover and experience basic heat transfer concepts. This week is now for you to design an experiment yourself.

Use your heat flux system to make some novel measurements. You simply need to record your data and then provide interpretation. Specifically, give a short description of your experiment (less than one page typed), including the following elements:

1. Background and motivation
2. Procedure
3. Results
4. Interpretation

This is your chance to be innovative and creative. Don’t be afraid to try something new and different. Attach appropriate figures and graphs.