

CHE 253M

Experiment No. 1

Temperature Measurement

Temperature is probably the most important and most measured property in science and engineering. Many different temperature-measuring devices have been devised and are in common use today. Each device has its own strengths and weaknesses, and is generally designed for a fairly specific application. As an engineer, it is important for you to select the best possible instrument for the job at hand.

This experiment is divided into two parts. In the first part, you will use and examine the accuracy and precision of four different types of thermometers. These are: a liquid in glass thermometer (LIGT), a pyrometer, two thermocouples, and a platinum resistance thermometer (PRT). You should walk away with not only an appreciation for the wide range of temperature measuring instruments available, but also a sense of the limitations of each. Further, you should become aware of the statistical nature of measurement and the myriad variables that can affect accuracy and precision.

In the second part we will use thermocouples first in a calorimetry experiment to determine the specific heat capacity of a metal, and then in a separate experiment to calculate the convection heat transfer coefficient of an aluminum plate as it cools from an initial high temperature to a lower temperature via free convection.

Measuring Temperature – A Brief Historical Background

Galileo is credited with inventing the thermometer, circa 1592. In an open container filled with colored alcohol, he suspended a long narrow-throated glass tube whose end was shaped into a hollow sphere – sort of like an upside-down thermometer. When the hollow sphere was heated, the air inside it expanded and bubbled through the liquid at the bottom of the tube. Conversely, cooling the sphere caused the liquid to move up inside the tube. Therefore, fluctuations in the temperature of the sphere could be quantified by noting the position of the liquid inside the glass tube. This “upside-down” thermometer was a poor indicator since the level changed with barometric pressure and the tube had no scale. A major improvement in temperature measurement accuracy was achieved with the introduction of the Florentine thermometer that incorporated a sealed tube construction and a graduated scale.

In the ensuing decades, many thermometric scales were conceived, all based on two or more fixed points. One scale, however, was not universally recognized until the early 1700’s when Gabriel Fahrenheit, a Dutch instrument maker, produced accurate and repeatable mercury thermometers. For the fixed point on the low end of his scale, Fahrenheit used a mixture of ice water and salt (or ammonium chloride). This was the lowest temperature he could reproduce, and labeled it “zero degrees.” For the high end of his scale, he chose human blood temperature and called it 96 degrees.

Why call it 96 and not 100 degrees, you might ask? It turns out that earlier scales had been divided into 12 parts. Fahrenheit, in a quest for more scale granularity, divided his scale into 24, then 48, and eventually 96 parts.

Around 1742, Anders Celsius proposed that the melting point of ice and the boiling point of water be used for the two benchmarks. Celsius actually chose the boiling point as zero degrees and the ice melting point as 100 degrees. After his death in 1744, the end points were reversed and the centigrade scale was born. In 1948, the name was officially changed to the Celsius scale that we are familiar with today.

In the early 1800's, William Thomson (Lord Kelvin), developed the universal thermodynamic scale based upon the coefficient of expansion of an ideal gas. Kelvin also introduced the concept of absolute zero and his scale remains the standard for modern thermometry. In 1954, the degree Celsius and the Kelvin were slightly redefined relative to absolute zero and the triple point of water (defined exactly as 0.01 °C and 273.16 K).

For purposes of practical use and calibration of thermometers, the International Temperature Scale of 1990, or ITS-90, was invented to closely follow the Kelvin scale. It is defined by numerous fixed points such as the triple point of hydrogen (13.8 K), the triple point of water (273.16 K) and the freezing points of aluminum and copper (933.5 K and 1357.8 K, respectively). The temperature between these points is defined by interpolation. Since the scale is determined by more than two points, it is overdetermined, but it is advantageous for calibrating thermometers that measure temperatures very different from the defining points of the Celsius and Kelvin scales. For instance, if the thermometer only has a range from 30–200 K, this scale allows a calibration.

Table 1

Temperature	Kelvin	Celsius	Fahrenheit
Absolute zero	0	-273.15	-459.67
Lowest recorded surface temperature on Earth (Antarctica - 1983)	184	-89	-128.2
Fahrenheit's ice/salt mixture	255.37	-17.78	0
Water freezes (at standard pressure)	273.15	0.00	32
Triple point of water	273.16 ²	0.01 ²	32.018
Average surface temperature on Earth	288	15	59
Average human body temperature ¹	309.95	36.8	98.24
Highest recorded surface temperature on Earth (Libya - 1922)	331	58	136.4
Water boils (at standard pressure)	373.13	99.98	212
Titanium melts	1941	1668	3034
The surface of the Sun	5800	5526	9980

¹ Normal human body temperature is 36.8 °C ±0.7 °C (98.2 °F ±1.3 °F). The commonly given value 98.6 °F is simply the exact conversion of the nineteenth-century German standard of 37 °C.

² Exact by definition

Accuracy and Precision of Temperature Measuring Instruments

Liquid-in-glass Thermometers

Everyone is familiar with liquid-in-glass thermometers (LIGTs). As we saw above, the first known thermometers were of the LIGT type. Although they are decidedly “low tech” devices, LIGTs of extremely high accuracy and precision can be constructed today. The concept behind LIGTs is very straightforward: a liquid in a narrow sealed glass tube expands and contracts with temperature, and temperature is read by a scale alongside the tube. For a number of important reasons, the liquid is typically mercury, although alcohol and other organic liquids can also be used. Several criteria for the liquid must be met to make a good thermometer:

- Remains a liquid over a wide temperature range
- Has a low vapor pressure
- Has a linear expansion vs. temperature response
- Does not wet the glass
- Has a large expansion coefficient for sensitivity

Mercury is superior to organic liquids in all the above criteria except the last. However, mercury freezes at $-38.9\text{ }^{\circ}\text{C}$; to measure temperatures below this, organic liquids must be used. Unfortunately, mercury is a potent neurotoxin, so a broken mercury thermometer is an environmental hazard. Consequently, as of February 1, 2011, the National Institute of Standards and Technology no longer performs calibrations of mercury thermometers.

Although they are seemingly simple devices, many subtle details must be incorporated into the design of LIGTs to insure accuracy, fast response, sensitivity, and durability. For example, uniformity of the bore diameter is critical for accuracy. Of course, as temperature increases, the glass expands, and the bore size slightly increases. This effect must be taken into account in high accuracy thermometers.

The thermometer we will be using in this experiment has been calibrated against a standard at the National Institute of Standards and Technology (NIST). A calibration certificate was shipped with the thermometer that certifies the thermometer’s accuracy as $\pm 0.01\text{ }^{\circ}\text{C}$ within the temperature range of 0 to $100\text{ }^{\circ}\text{C}$.

Thermocouples

In 1821, Thomas Seebeck discovered that when two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, a continuous current will flow across this *thermoelectric* circuit (Figure 1).



Figure 1

If this circuit is broken at the center, the net open circuit voltage (the Seebeck voltage) is a function of the junction temperature and the composition of the two metals (Figure 2).



Figure 2

By measuring the so-called “Seebeck Voltage” across the open circuit, the temperature can be determined by the equation:

$$\Delta e_{AB} = \alpha_{AB} T \quad (1)$$

where the proportionality constant, α_{AB} , is the Seebeck coefficient for metals A and B (V/K), and T is the absolute temperature.

Measuring Thermocouple Voltage

We cannot measure the Seebeck voltage directly because we must first connect a voltmeter to the thermocouple, *and the voltmeter leads themselves create a new thermoelectric circuit*. To illustrate this, let’s connect a voltmeter across a copper-constantan (Type T) thermocouple as shown in Figure 3, and look at the voltage output: We would like the voltmeter to read only V_1 , but by connecting the voltmeter in an attempt to measure the output of Junction J_1 , we have created two more metallic junctions: J_2 and J_3 . Since J_3 is a copper-to-copper junction, it creates no thermal EMF ($V_3 = 0$), but J_2 is a copper-to-constantan junction which will add an EMF (V_2) in opposition to V_1 . The resultant voltmeter reading V will be proportional to the temperature difference between J_1 and J_2 . This says that we cannot find the temperature at J_1 unless we first find the temperature of J_2 .

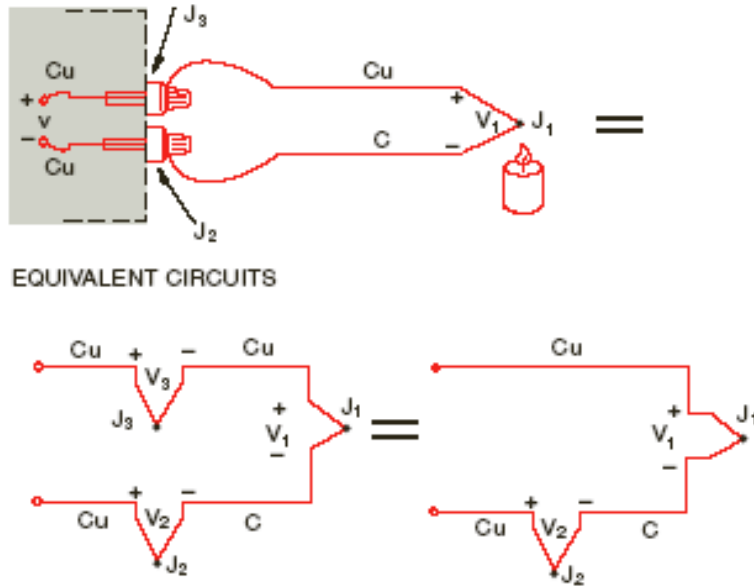


Figure 3

One way to determine the temperature of J2 is to physically put the junction into an ice bath, forcing its temperature to be 0 °C and establishing J2 as the Reference Junction. Since both voltmeter terminal junctions are now copper-copper, they create no thermal EMF and the reading V on the voltmeter is proportional to the temperature difference between J1 and J2 (Figure 4, below).

Now the voltmeter reading is:

$$V = (V_1 - V_2) = \alpha(T_{J_1} - T_{J_2}) \quad (2)$$

If we specify T_{J_1} in degrees Celsius:

$$T_{J_1}(\text{°C}) + 273.15 = T_{J_1} \quad (3)$$

then V becomes:

$$\begin{aligned} V &= V_1 - V_2 = \alpha[(T_{J_1}(\text{°C}) + 273.15) - (T_{J_2}(\text{°C}) + 273.15)] \\ &= \alpha[T_{J_1}(\text{°C}) - T_{J_2}(\text{°C})] = \alpha[T_{J_1}(\text{°C}) - 0] = \alpha T_{J_1}(\text{°C}) \end{aligned} \quad (4)$$

We use this protracted derivation to emphasize that the ice bath junction output, V_2 , is *not* zero volts. It is a function of absolute temperature. By adding the voltage of the ice point reference junction, we have now referenced the reading V to 0 °C. This method is very accurate because the ice point temperature can be precisely controlled. The ice point is used by the National Institute of Standards and Technology (NIST) as the fundamental reference point for their thermocouple tables, so we can now look at the NIST tables and directly convert from voltage V to temperature T_{J_1} .

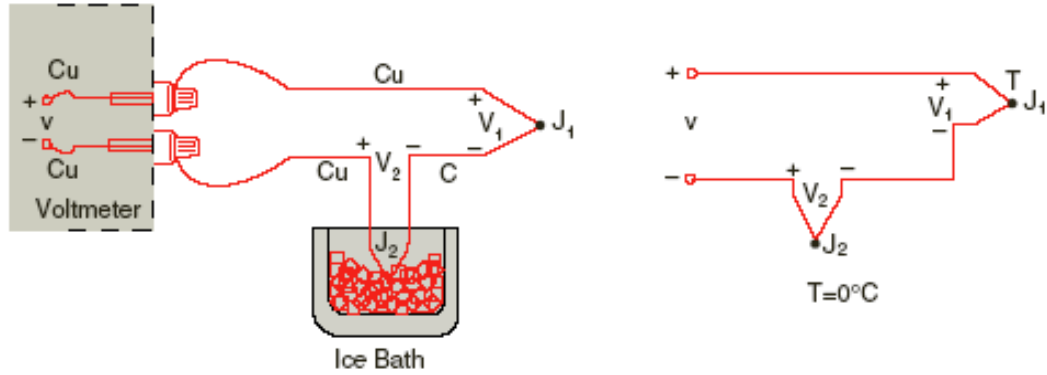


Figure 4

We do not actually use an ice bath every time we take a temperature measurement with a thermocouple. Instead, we measure the reference junction temperature, using a sensor other than a thermocouple, and compensate for its effect on the thermocouple voltage either electronically or in software. This is called "reference junction compensation."

Thermocouples are designated by letter to indicate the types of metals used in them. In this experiment, we will be using J, K, and T type thermocouples. Each type has a standard connector color. The table below lists the composition of each thermocouple and their connector colors. The three thermocouples generate approximately $38\text{-}50\ \mu\text{V}/^\circ\text{C}$ in the temperature range being used in our experiment. Thermocouple charts of voltage vs. temperature can be found in the CRC Handbook of Chemistry and Physics.

Table 2

Type	+ Wire	- Wire	Connector
J	Iron	Constantan	Black
K	Chromel	Alumel	Yellow
T	Copper	Constantan	Blue

Constantan, Alumel, and Chromel are trade names for specific alloys: Constantan: 55% Cu, 45% Ni; Alumel: 95% Ni, 2% Mn, 2% Al, 1% Si; Chromel: 84.5% Ni, 14.2% Cr, 1.4% Si (all percentages are by weight). These alloys and metals have been chosen because they have large Seebeck coefficients. The larger the Seebeck coefficient, the more sensitive the thermometer is.

Resistance Thermometers

Most metals exhibit an increase in their electrical resistance as their temperature is increased. Although a variety of metals can be used, platinum has become the metal of choice for precision resistance thermometers. It offers a large measuring range, is very stable, and has a linear resistance vs. temperature curve. Platinum resistance thermometers (PRTs) are typically made of a thin coil of platinum wire placed in a protective

sealed metal or glass sheath. The sheath serves to guard the element against contamination, oxidation, and mechanical strain.

Our PRTs are made so that their resistance-temperature curves approximately coincide with the ITS-90 standard platinum resistance thermometer coefficients. The thermometer's resistance has been made so that it is 100 Ω at 0°C.

Of course, other materials have electrical resistance and can be used to measure temperature. The other most common resistance thermometers use polymers or doped ceramic materials and are termed *thermistors*. Because they are semiconducting, their resistance is usually larger and varies tremendously over a short temperature range, leading to greater resolution. However, they are generally only useful over a short range.

Infrared Thermometers

Infrared thermometers, or pyrometers, read temperatures by measuring the intensity of infrared radiation emitted from an object. Because they provide a non-contact method of measurement, they can be used to measure extremely high temperatures. In addition, because they do not need to equilibrate to the temperature they are measuring, they can have very rapid response times. Pyrometers are useful in situations where actually contacting the object to be measured is impractical or impossible. An example is the "ear thermometer" available in drug stores. It is a pyrometer that measures the temperature of the eardrum.

The theory behind pyrometers is based on Planck's law for a blackbody radiator. A blackbody radiator is an object which absorbs all incident radiation and emits radiation in a spectral distribution that depends on its temperature. All objects above 0 K emit some amount of thermal radiation. The radiation is not emitted at a single wavelength, but over a range of wavelengths that can be described by Planck's famous equation:

$$W(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\left(e^{\frac{hc}{\lambda kT}} - 1\right)} \quad (5)$$

where: W = radiant power intensity over a hemisphere (energy/volume)
 h = Planck's constant = 6.626×10^{-34} J·s
 c = speed of light in a vacuum = 2.998×10^8 m/s
 λ = wavelength of radiation emitted
 k = Boltzmann's constant = 1.38×10^{-23} J/K
 T = absolute temperature of radiator

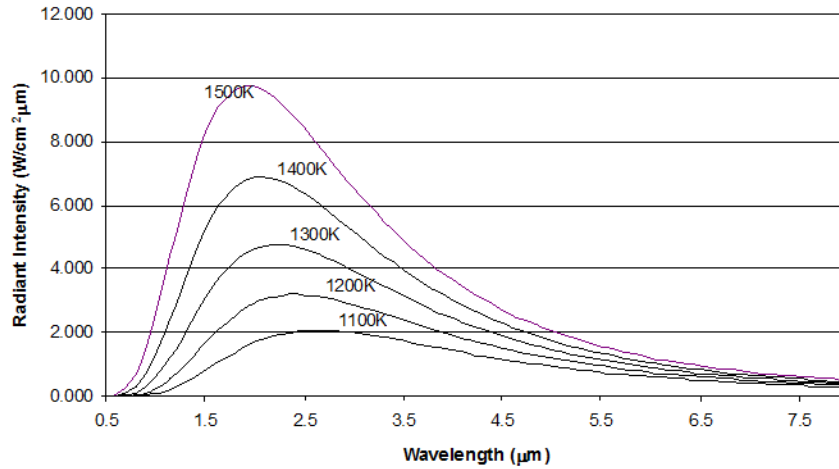


Figure 5: Planck's law for a blackbody radiator

Figure 5 shows a plot of the output of several blackbody radiators at different temperatures. Planck's law is only valid for blackbody radiators, which do not exist in nature (all objects will reflect or transmit a certain amount of incident radiation). To correct for this, a material property called emissivity is used. Emissivity is defined as:

$$\varepsilon = 1 - r - t \tag{6}$$

where r and t are reflectance and transmittance. Thus, for a blackbody, ε will be 1; all other objects will have an emissivity < 1 . If an opaque object is being measured, then t can be neglected. Multiplying Planck's Law by emissivity of a non-blackbody radiator will approximate the output of the object.

Integrating Planck's Law over the entire spectrum gives the Stefan-Boltzmann Law:

$$W = \sigma T^4 \tag{7}$$

where σ is the Stefan-Boltzmann constant, 5.6687×10^{-8} J/K⁴·m²·s. This law gives the power output of the radiator across the whole spectrum. Multiplying the right hand side by the emissivity will give the total energy flux for a non-blackbody radiator.

$$q_R = \varepsilon \sigma T^4 \tag{8}$$

Note: For a blackbody radiator inside a cavity (such as a lab with walls at temperature T_l), the net radiated energy is approximately (see BSL §16.5) the flux output minus the absorbed input from the cavity, times the area:

$$Q_{R,net} = \varepsilon \sigma A (T^4 - T_l^4) \tag{9}$$

Our pyrometer works by measuring the spectral emission of an object between 8 and 14 μm of wavelength range and comparing it to the Stefan-Boltzmann and Planck laws. The emissivity of the object being measured must be known and entered into the pyrometer. Thus, the accuracy of the temperature measurement is highly dependent on how well you know the emissivity. Oxidation, dirt, and other surface deposits will all affect the emissivity of an object. In addition, emissivity will change with viewing angle, wavelength, and temperature. The temperature measurement of shiny, highly reflective metal surfaces in particular is always problematic for infrared thermometers due to their low emissivity.

Calorimetry - Specific Heat Capacity

Heat capacity (symbol C , also called thermal capacity) is the ability of matter to store heat. The heat capacity of a certain amount of matter is the quantity of heat (measured in joules) required to raise its temperature by one Kelvin. The specific heat capacity (symbol c or s , also called specific heat) of a substance is defined as heat capacity per unit mass, or the amount of heat energy required to raise the temperature of one kilogram of the substance by one Kelvin. The SI derived unit for specific heat capacity is the *joule per kilogram Kelvin*, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ or $\text{J}/(\text{kg}\cdot\text{K})$.

Heat capacities are commonly measured using calorimetry. Calorimeters are designed to be adiabatic, in other words they are very well insulated so that no heat is gained from or lost to the surroundings. If no heating element is used to introduce heat in the system, the total heat transferred (Q) for the entire calorimeter system must equal zero. The total heat can be split into heats for each component in the system.

Imagine an experiment in which a piece of metal (aluminum, for example) is heated to a specific temperature and then dropped into a calorimeter containing water at room temperature. The aluminum will lose heat, which will be absorbed by the water. Because no heat enters or leaves the system from the calorimeter, the heat balance is

$$0 = Q = Q_{Al} + Q_W \quad (10)$$

In this example, Q_{Al} is negative, because the aluminum will lose heat to the water, and $Q_W > 0$ because the water will gain heat.

After the system reaches equilibrium, all substances will have the same final temperature (T_f) even though not all substances started with at the same initial temperature. The aluminum was initially at temperature T_{Al} while water was initially at temperature T_i .

$$Q_{Al} = m_{Al}c_{Al}(T_f - T_{Al}) \quad (11)$$

$$Q_W = m_Wc_W(T_f - T_i) \quad (12)$$

The specific heat capacity of water is known ($4184 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$), and the temperatures T_{Al} , T_i , and T_f , as well as the masses of the aluminum and water (m_{Al} and m_W) can be measured experimentally. The only unknown property in the above equations is the specific heat capacity of the aluminum,

$$c_{Al} = -\frac{m_Wc_W(T_f - T_i)}{m_{Al}(T_f - T_{Al})} \quad (13)$$

Transient Heat Transfer: Calculation of the Convection Heat Transfer Coefficient for a Vertical Plate

Theoretical Background

In this part of the experiment you will determine the convection heat transfer coefficient (h) of a metal (aluminum) plate suspended vertically, by measuring the ambient temperature of the room and the surface temperature of the plate as it cools from an initial high temperature to a lower temperature via free convection.

Recall the first law of thermodynamics which states that the change in internal energy of a system (ΔU) is equal to the heat added to the system (Q), minus the work done by the system (W)

$$\Delta U = Q - W \quad (14)$$

Now consider an object that is surrounded by an infinite, constant temperature (T_∞) heat sink such as the one shown in Figure 6 below. In this case the work term is zero, and the first law of thermodynamics becomes

$$Q = \Delta U = \frac{dU}{dt} \quad (15)$$

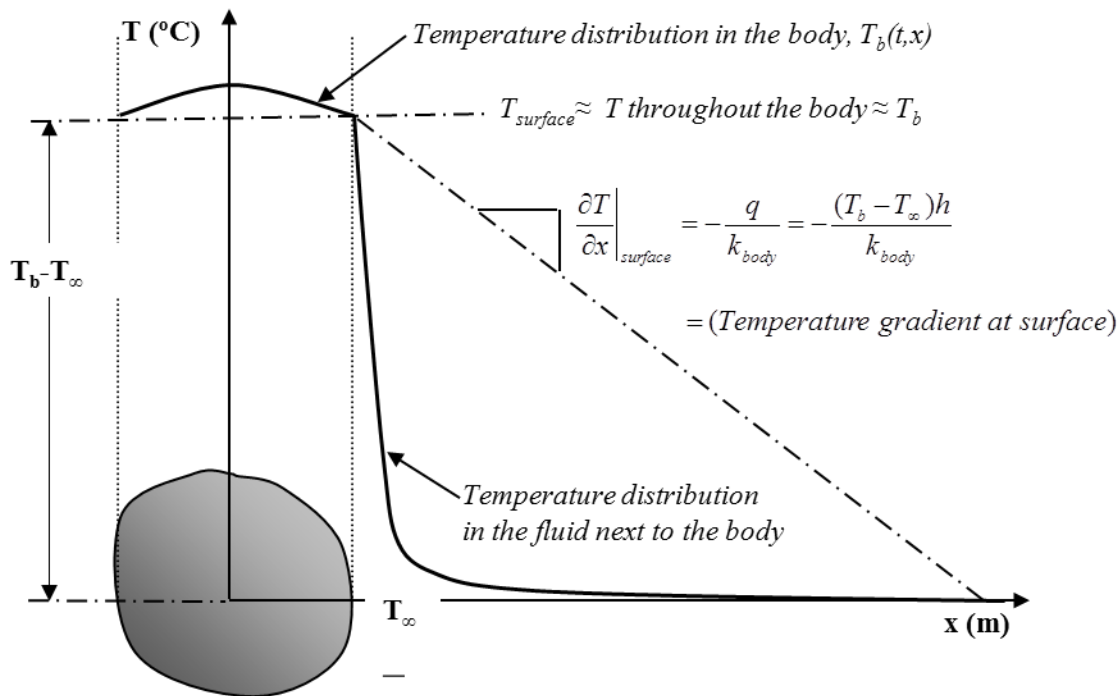


Figure 6

At a solid-fluid interface, the rate of heat flow (Q) can be related to the difference between the temperature at the interface and that in the fluid (“Newton’s Law of Cooling”),

$$Q = -hA(T - T_\infty) \quad (16)$$

The change in internal energy is

$$\frac{dU}{dt} = \frac{d[mcT]}{dt} = \frac{d[\rho VcT]}{dt} \quad (17)$$

where A , V , ρ , T , c , and h are the surface area, volume, density, temperature, the specific heat capacity, and the mean (or average) heat transfer coefficient for the body, respectively. Equating the right hand side of equations (16) and (17) and rearranging, we get the simple differential equation,

$$\frac{dT}{dt} = -\frac{hA}{\rho cV}(T - T_\infty) \quad (18)$$

The general solution is

$$\ln(T - T_\infty) = -\frac{t}{\frac{\rho cV}{hA}} + \mathbb{C} \quad (19)$$

The group $\frac{\rho cV}{hA}$ is the time constant, τ . If the initial body temperature is $T(t = 0) \equiv T_i$ then $\mathbb{C} = \ln(T_i - T_\infty)$ and the cooling of the body is given by

$$\frac{T - T_\infty}{T_i - T_\infty} = e^{-\frac{hA}{\rho cV}t} = e^{-t/\tau} \quad (20)$$

Notice that thermal conductivity is missing from Equation(20). The reason is that we have assumed that the temperature of the body is uniform (i.e. the surface temperature is very close to the center-line temperature) and this means that internal conduction is not important. Resistance due to conduction from the center to the surface is negligible compared to the resistance of convection to the surroundings. Hence, the combined resistance can be “lumped” together without great error and this is known as the lumped heat capacity heat transfer model.

An exact model would assume that the temperature profile across a cooled solid is not negligible from center to surface. To determine the applicability of the lumped model, the *Biot number* (Bi) is used. The Biot number is a dimensionless ratio of an object’s internal conduction resistance to its external convective resistance. If the value of Bi is less than 0.1, then the lumped heat capacity model is applicable. Otherwise, the exact solution is necessary. The Biot number is

$$\text{Bi} = \frac{hL_c}{k} \quad (21)$$

where k is the thermal conductivity, and L_c is the characteristic length,

$$L_c = \frac{\text{Volume}}{\text{Area}} = \frac{V}{A} \quad (22)$$

Experimental Procedure

Please bring a USB flash drive to store your experimental data. You can also email yourself the data. The order of experiments is a suggestion only.

1. **Thermocouple Resolution and Precision:** Investigate the resolution and precision of two thermocouples by measuring the temperature of a Hotplate via the side-mounted thermocouples. First, double-click on the “**Hotplate**” icon on the Windows desktop. This LabVIEW program allows you to control and monitor the hotplate’s temperature. Set the hotplate’s temperature to 60 °C and turn it on. Once you start the software, flip the toggle switch to turn the power on to the main control box. When the temperature has stabilized, record temperatures from the K-type and T-type thermocouples *at least* 30 times at regular intervals. LabVIEW will store the results in an Excel file for you. Switch off the hotplate when you are finished.
2. **Emissivity and Thermometer precision:** Before coming to lab, download and read the manual for the Extech pyrometer you will use. Set emissivity ≈ 0.98 for water, aim the pyrometer at a water bath, and measure its temperature. Each member of your group should take a turn using the pyrometer. Adjust the size of the pyrometer’s target by moving it closer to or further from the surface and. Also, try changing the angle between the pyrometer and the surface. **Please Note:** Do not stare into the beam

We will use the pyrometer and two surface-mounted thermometers to compare precision between the methods and thermometers. Launch the “**Emissivity and Surface Temperature**” LabVIEW program, set the hotplate temperature to 55°C, and place a chosen sample block (several materials are available) equipped with the surface-mounted probes on the hotplate. When hotplate and sample have equilibrated (how will you know?), aim the pyrometer at the sample, measure the temperature and adjust the emissivity value until the temperature read by the pyrometer matches the set temperature. Record this emissivity value, which will be used in subsequent measurements.

Finally, measure the temperature of the heated block multiple times (you should decide on the number of measurements before starting the experiment!) with both the pyrometer and the surface thermocouple. The surface thermocouple temperatures can be logged automatically using the LabVIEW program. Repeat the measurements at hotplate temperatures of 65, 75, and 85 °C.

3. **Thermometer Calibration:** Calibrate the liquid-in-glass thermometer and the K- and T-type thermocouples with the NIST standard platinum resistance thermometer. Prepare four baths at 0, 23, 50, and 75 °C. The 0 °C bath can be made by filling a Dewar flask with crushed ice and distilled water (DI). Watch the video at <http://www.epa.gov/hg/nistvideo/index.html#icepoint> before you come to lab to learn how to make an ice point with minimal uncertainty. Make the 23 °C bath by letting DI water equilibrate at room temperature (it is understood that the temperature will not be exactly 23 °C). The 50 °C and 75 °C baths are available in the laboratory and

are electronically heated by thermostatic control. The multimeter will measure the resistance of the PRT and convert this to a temperature reading that you can record. You can use the “**Calibrate**” program on the computer to read the thermocouple temperatures. Immerse all 4 thermometers in each bath at the same time and get the readings simultaneously. Measure the temperature *at least* 4 times for each bath. **Please Note:** The NIST thermometer is an extremely accurate instrument and **very expensive and very delicate**. Return it to its protective case when you are finished.

4. **Calorimetry – Specific Heat Capacity:** First record the weight of the cylindrical piece of aluminum whose specific heat capacity is to be determined. Place the aluminum piece in the 75°C water bath and let it sit for at least 2 minutes to fully reach the temperature of the water bath. Carefully weigh approx. 100 mL of water in a Styrofoam cup and record the mass. Pour the water into the Dewar flask and place the K-type (yellow) thermocouple probe to record the temperature. Use the “**Heat Capacity**” software on the computer to monitor the temperature change. Remove the piece of aluminum from the water bath, and promptly (and very CAREFULLY) place it in the water inside the Dewar flask. Gently stir the flask and record the temperature at which the water stabilizes (how will you know when this occurs?) Repeat this measurement *at least* 3 times.
5. **Convection Heat Transfer:** Using the caliper, measure the exact dimensions of the first sample plate; the weight of the plate will be given. The plate has an embedded thermocouple. It is small, so you can ignore its effect on heat capacity and transfer. The caliper has a vernier scale. **Before coming to lab**, watch this short video on youtube on vernier caliper use: <http://www.youtube.com/watch?v=Vz40xmrdhyY> and read about vernier calipers on Wikipedia. From your measurements, calculate the density of the plate, and check it against the given value. Set one of the water baths to 75 °C. Arrange supports and clamps on the lab bench framework so you can vertically suspend the plate (a) immersed in, and (b) away from the hot water bath. Start the “**Heat Transfer**” program to monitor plate temperature. Carefully lower the plate into the hot water. Tighten the metal clamp in place, and let the plate sit in the water until its temperature is close to 75°C. Quickly raise the plate and suspend it in mid-air on the support away from the bath, making sure the plate is suspended vertically. Start data collection at a rate of one point every 10 seconds. Stop the data acquisition when the temperature of the plate has reached 45°C.

Notes: (1) Handle the thermocouple-plate assemblies carefully, because the weight of the plate can bend the thermocouple. Plan and rehearse moving the plate from the hot water bath to the free convection hanger. (2) You may perform the other experiments while waiting on data collection for Convective Heat Transfer. Minimize, but do not close, the “Heat Transfer” program before you start another LabView program.

Lab Write-Up: Results Section

Notes: JMP must be used. Look in the appendix for any material constants and/or tables you might need for your data analysis.

- 1. Thermocouple Resolution and Precision:** Make plots of temperature vs. time, lag plots (T_i vs. T_{i-1}), histograms, and normal quantile plots (using JMP, for instance) for both the K- and T-type thermocouples. Calculate the sample means and standard deviations, and find 95% confidence limits for the mean temperature calculated for each thermocouple. Compare the two variances by using an F Test (see <http://www.itl.nist.gov/div898/handbook/eda/section3/eda359.htm>).

Discussion: Discuss the relative precision of the K and T-type thermocouples based on the measurements taken in Part 1 of the experiment. Is there a significant difference between the two thermocouples based on your results? How do you know? Also discuss what you learn about the data from each plot. Is the data normally distributed?
- 2. Emissivity and Thermometer Precision:** Report the emissivity value. Compute the sample mean and standard deviation for the surface thermocouples and the infrared thermometer at each temperature.

Discussion: Discuss the precision of the three thermometers. Order them in terms of precision. Does the precision of any of the thermometers change with temperature? If so, give reasons why this occurs for each thermometer.
- 3. Thermometer Calibration:** Report the calibration equations for the two thermocouples and the liquid in glass thermometer in the form of $y = mx + b$, where x is the mean temperature of the standard, y is the temperature of the instrument being calibrated, m is the calibration slope, and b is the calibration intercept. Report the 95% confidence limits for the slopes and intercepts, and report the standard error for the fits. For each fit, plot the residuals against nominal temperature (i.e. $T_{\text{expt}} - T_{\text{fit}}$ v. T) and make a normal quantile plot of the residuals. From the calibration data, generate a plot of $(T_{\text{expt}} - T_{\text{NIST}})$ v. T_{NIST} for each thermocouple and for the LIGT. (Plot all three on one graph. This lets you compare overall accuracy visually.)

Discussion: Discuss the equation coefficients and their uncertainties in relation to the relative precision and accuracy of the thermometers.
- 4. Calorimetry – Specific Heat Capacity:** Calculate and report the mean specific heat capacity of aluminum (c_{Al}) along with the sample standard deviation. Calculate a 95% confidence limit for the mean value based on this sample standard deviation.

Discussion: Compare the experimentally determined average value for the specific heat capacity of aluminum with the literature value of $c_{Al} = 897 \text{ J kg}^{-1} \cdot \text{K}^{-1}$. Is the literature value within the 95% confidence limits of the calculated value? Do the confidence limits have any implication on the overall accuracy of the measurement? Explain in detail specific sources of error associated with the lab procedure. For each possible source of error, estimate the magnitude and direction of the effect it might have on the calculated heat capacity. How could the procedure be modified to give more accurate results?
- 5. Convection Heat Transfer:** (i) Calculate and report the time constant (τ) and its 95% confidence limits. To do so, you need to rearrange Equation (20) to obtain a linear equation with slope related to the time constant, and fit this equation to your data.

Remember to adjust the data so that at $t = 0$, $T = T_i$ and use the average room temperature as the constant T_∞ . Plot the residuals of the fit vs. time, and calculate the 95% confidence interval for τ . (ii) Calculate the heat transfer coefficient (h) from the expression for the time constant you calculated above. Use the experimental value of c_{Al} from part 4 above and any other material constants you have measured in the experiment. Also, calculate the uncertainty (i.e. 95% confidence limits) in the measurement of h using propagation of uncertainty and the uncertainty in your measurement of V_2 , A , and c_{Al} . (iii) Calculate the Biot number. (iv) On one figure, plot the **experimental** T vs. t data as well as three **theoretical** T vs. t curves calculated using the estimated value of h and the upper and lower confidence limits for h . (v) Calculate the instantaneous power lost by the plate at the start of cooling (i.e. at time T_i) by convection (Q_c) and by radiation (Q_R). Hint: See equations (9) and (16) and use an emissivity of 0.1.

Discussion: Does the value of the Biot number justify the applicability of the lumped heat capacity model in this experiment? Discuss the plot of the fit residuals vs. time: are there any irregularities or outliers? Is the radiation loss significant compared to the convective loss in this experiment? Can you use the radiation loss to explain the shape of the experimental T vs. t curve compared to the theoretical one?

Sample Calculations:

- 1) Show the calculations used for the linear regression analysis and confidence limits (for both the slope and the intercept) for any **one** calibration curve.
- 2) Clearly show how you calculated all of the following: [c_{Al} , τ , h and its uncertainty, Bi , (Q_c), (Q_R)]