Heat Transfer
(Heat and Thermodynamics)

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If you put one end of a spoon on the stove and wait for a while, your finger tips start feeling the burn. So how do you explain this simple observation in terms of physics?

Heat is generally considered to be thermal energy in transit, flowing between two objects that are kept at different temperatures. Thermodynamics is mainly concerned with objects in a state of equilibrium, while the subject of heat transfer probes matter in a state of disequilibrium. Heat transfer is a beautiful and astoundingly rich subject. For example, heat transfer is inextricably linked with atomic and molecular vibrations; marrying thermal physics with solid state physics—the study of the structure of matter.

We all know that flowing matter (such as air) in contact with a heated object can help ‘carry the heat away’. The motion of the fluid, its turbulence, the flow pattern and the shape, size and surface of the object can have a pronounced effect on how heat is transferred. These heat flow mechanisms are also an essential part of our ventilation and air conditioning mechanisms, adding comfort to our lives. Importantly, without heat exchange in power plants it is impossible to think of any power generation, without heat transfer the internal combustion engine could not drive our automobiles and without it, we would not be able to use our computer for long and do lengthy experiments (like this one!), without overheating and frying our electronics. Heat transfer is also an integral component of the global climatic cycle, affecting how the human civilization has demographically placed itself on the globe and what lifestyles and customs have evolved around geographical habitats. Finally, global warming is a slow poison that will, in part, determine our future destinies.

KEYWORDS

Internal Energy · Temperature · Conduction · Convection · Radiation · Black Body Radiation · Newton’s Law of Cooling · Stefan-Boltzmann Law · Thermocouple · Data Acquisition

APPROXIMATE PERFORMANCE TIME 4 hours
1 Conceptual Objectives

In this experiment, we will,

1. understand different modes of heat transfer and identify regimes in which one mode dominates over the other;
2. identify the role of thermally conducting and insulating materials;
3. learn about temperature measurements using thermocouples;
4. learn how surface modification can change the properties of an object;
5. practice interfacing sensors and signal condition systems to the PC;
6. corroborate experimental results with theoretical predictions;
7. mathematically model natural processes;
8. appreciate the role of approximations in experimental science; and
9. calculate the propagation of errors from observed to inferred quantities.

2 Experimental Objectives

In the present experiment, we heat an object and observe how it cools with time and what factors affect the cooling rate. We adapt the experimental setup to interchange between two different environments. In one section, we allow the object to be cooled with the help of forced air currents and in the other, the system is made to act like a black body cavity. We will also learn how to use the thermocouple, an important component of numerous commercially important processes.

3 Theoretical Introduction

3.1 Thermal conduction

We already know that atoms or molecules in a solid vibrate all the time, and that temperature is proportional to the kinetic energy of the molecules or atoms. Coming back to the question we asked at the very beginning, the atoms and electrons at the fire end of the spoon start to vibrate with a higher amplitude. These more energetic atoms, interact with the neighbouring atom and transfer some energy to them every time they collide. This process carries on along the length of the spoon (atom to atom) and after a while the energy reaches our brain through thermal receptors in our skin. When we talk of conduction, we always conjure up the notions of atomic and molecular activity.

Conduction is the process whereby heat energy is transferred across a medium. There are materials which are good or poor conductors of heat just like there are materials which are good or bad conductors of electricity.
Suppose one end of a copper slab is heated to a temperature $T_2$, while the other end is kept fixed at a lower temperature $T_1$. Heat flows from the hot to the cold end. Suppose $Q$ is the power transmitted (in W). The area perpendicular to the direction of heat propagation is $A$ and the length between the two ends of the slab is $L$ (see Figure 2). We want to mathematically model this simple process (Figure 2) keeping in mind that the power transmitted is proportional to the area $A$, the temperature difference $T_2 - T_1$ and inversely proportional to the length $L$. The equation (under steady state conditions) is,

\[ Q_{\text{cond}} = -kA \frac{(T_2 - T_1)}{L}. \]  

(1)

Sometimes, this equation is also written as,

\[ q_{\text{cond}} = -k \frac{(T_2 - T_1)}{L}. \]  

(2)

where $q_{\text{cond}}$ is the power density (units are $W \text{ m}^{-2}$), the heat energy transferred per unit area per unit time.

![Figure 1: Conductive transfer of heat from the hot to the cold end of a rod. The power transmitted is $Q$ through an area $A$ and across a length $L$.](image)

**Q 1.** What are the SI units for the *conducitivity*, $k$? What is the physical meaning of $k$?

**Q 2.** A glass window is 5 mm thick. The inner and outer surfaces have temperatures of 25° C and 40° C. At what rate is the inner surface heated if the window is 1 m by 1 m on the sides? The conductivity of glass is 1.4 $W \text{ m}^{-1} \text{ K}^{-1}$.

### 3.2 Thermal convection

Suppose you are driving your car in a hot June afternoon. You bend over a bit to see the air above your car’s hood. Why does the background seem so hazy? The observation is a result of a process called *convection* and it occurs when a moving fluid comes in contact with an object whose temperature is higher than that of the fluid itself. When the less energetic molecules of the air come in contact with the fast vibrating molecules of the hood, they undergo collisions, picking up
energy from the hot surface of the hood. At the intimate interface of the hood and the air, the process is exactly similar to conduction. But the temperature of the air soon rises at the surface, the density decreases and the molecules have become more buoyant, causing the hot air to rise. These molecules then transfer the thermal energy to neighboring molecules through collisions (conduction) as well as through the bulk flow of air (convection). In practice, both of these modes of heat transfer go on, hands in hand [1]. Which process dominates is determined by the shape of the heated object and the flow velocity and profile of the fluid.

Convection is also seen at the global scale when it rains. In fact in Lahore, we all eagerly await the Monsoon season. It is the process of convection that transports the thermal energy from the hot land surfaces to the atmosphere. The rising hot air on the land creates a low pressure region that sucks air laden with condensed water vapour from above the Bay of Bengal and the Arabian Sea. By the time clouds reach the land mass, they gradually rise to higher and higher altitudes, the moisture is condensed and the clouds finally lay their watery burden onto the thirsty land.

### 3.3 Newton’s law of cooling

The analogous equation to (1) for the process of convection is,

$$Q_{\text{conv}} = hA(T_2 - T_1),$$  \hspace{1cm} (3)

and in terms of power density,

$$q_{\text{conv}} = h(T_2 - T_1).$$  \hspace{1cm} (4)

Here $T_2$ is the temperature of the hot object and $T_1$ is the temperature of the fluid far away from the object. The units of $Q_{\text{conv}}$ are watts and $h$ is called the coefficient of convective heat transfer. Equation (3) is sometimes referred to as Newton’s law of cooling.

![Diagram](image)

**Figure 2:** Setting for Newton’s law of cooling. The power transmitted from a rod of surface area $A$ is $Q$. The surface is at a steady temperature of $T_2$ and $T_1$ is the temperature of a mass of air far away.

**Q 3.** What are the units of $h$? How do these compare with the units of $k$?
Amongst several other tasks, this experiment will help us determine (a) how $T_2$ varies with time, and (b) how $h$ varies with temperature. The value of $h$ depends on the properties and flow of the fluid, the temperature of the hot surface, the surface geometry as well as the bulk fluid velocity [1]. It is an empirical quantity.

Q 4. Hot air at 80°C is blown over a 2 x 4 m² flat surface at 30°C. If the average coefficient of convective heat transfer is 55 W m⁻² K⁻¹, determine the rate of heat transfer from the air to the plate [1].

3.4 Forced convection

Many electronic devices these days, computers included, come with cooling units. These are small fans that direct a stream of air onto the printed circuit board that is likely to get heated or the microprocessor. The increased air currents help the convection process, supplementing the density-assisted buoyant forces. Mathematically, forced convection, as it is called, changes the value of $h$. For example, for convection in still air, the value of $h$ could be $2 - 25$ W m⁻² K⁻¹ whereas this could go as high up to 250 if the air is in motion.

Interestingly, human bodies also produce heat. Ventilation systems in buildings are designed keeping in account the heat loads of human bodies. An average adult, even in a state of resting, has a certain basal metabolic rate (BMR). The process generates heat. The typical heat load is 90 W per person and this heat must be dissipated. For an average human surface area of 2 m², the flux of heat that must be transferred to the atmosphere is 45 W m⁻². We all know very well, that in summers, when it is very hot, it becomes increasingly difficult to dissipate this heat and hence most of us resort to the luxuries of forced convection. We must also remember that the human body has, in fact, developed a very sophisticated regulatory mechanism for this purpose.

Q 5. Air impinges onto a power transistor with a certain velocity, always maintaining a convective heat transfer coefficient $h$ of 100 W m⁻² K⁻¹. The temperature of the air is 25°C and the maximum temperature the transistor can withstand is 60°C. The diameter and length are 10 mm each. Calculate the maximum power dissipation of the transistor? (Adapted from [2].)

Q 6. You extend your hand outside a car moving at a speed of 60 km h⁻¹. The outside air temperature is 5°C and the air velocity results in a value of $h \approx 50$ W m⁻² K⁻¹. The skin temperature is 34°C, slightly lower than the normal internal body temperature. What is the maximum heat transfer rate this kind of forced convection can support? (Adapted from [2].)

3.5 Radiation (Stefan-Boltzmann law and cavity radiation)

There is yet another mode of heat transfer. This mode does not require the presence of any medium or molecular interactions and is called radiation.

Every object in nature radiates and absorbs electromagnetic waves, be it day or night. How does light and heat, from the Sun, reach us? Even when there is no (real) matter in the space in between. Why is it that even with a cool breeze on
the Clifton sea-front, the warmth of a bonfire keeps us cosy? The answer lies in radiation.

Radiation is a result of temperature. If a body is hotter than its surroundings it emits more radiation than it absorbs, and tends to cool; if a body is cooler than its surroundings it absorbs more radiation than it emits, and tends to warm. It will eventually come to thermal equilibrium with its surroundings, a condition in which its rates of absorption and emission of radiation become equal.

Suppose a solid object has a surface temperature $T_2$. The heat radiated per unit time is now denoted by $Q_{rad}$ and is given by,

$$Q_{rad} = \sigma A T_2^4, \quad (5)$$

or in terms of the heat radiated per unit area per unit time,

$$q_{rad} = \sigma T_2^4. \quad (6)$$

where $\sigma$ is a constant with a value of $5.67 \times 10^{-8}$ W m$^{-2}$K$^{-4}$, analogous to the $h$ we have discussed in the context of convection. This equation is generally referred to as the Stefan-Boltzmann law and an object respecting this condition is called a blackbody. A blackbody is a perfect emitter. Given a fixed temperature, no other object can emit more energy than a blackbody.

However, in practice, no real object is a perfect blackbody and the radiative power density $q_{rad}$ is decreased by a factor $\varepsilon$, called the emissivity. Equation (8) is modified to,

$$q_{rad} = \varepsilon \sigma T_2^4. \quad (7)$$

An ideal value of $\varepsilon = 1$ refers to an object that emits all of the available radiative energy.

Now suppose, we place another very large surface (call it $Q$) that completely encloses the object of interest (call it $P$), as shown in Figure 3. The surface $Q$ emits at a lower temperature $T_1$, the output power density being,

$$q_{rad} = \varepsilon \sigma T_1^4. \quad (8)$$

The net power density being transferred from $P$ to $Q$ becomes,

$$q_{rad} = \varepsilon \sigma T_2^4 - \varepsilon \sigma T_1^4 = \varepsilon \sigma (T_2^4 - T_1^4). \quad (9)$$

and the radiative power transmitted is,

$$Q_{rad} = \varepsilon \sigma A (T_2^4 - T_1^4). \quad (10)$$

Note that this power does not depend on the surface area of $Q$.

Q 7. Is every black surface a blackbody?

Q 8. What assumptions go into writing Equation (9)?

Q 9. Do you expect a silvered mirror to have a high or low value of emissivity?
Figure 3: A blackbody $P$ is placed inside another blackbody $Q$. The long arrows emanating outwards from $P$ represent the thermal power emitted by $P$ and the short arrows pointing inwards represent the thermal power absorbed by $P$.

Now suppose an object $P$ with emissivity $\varepsilon$ and surface area $A$ is heated to $T_2$ and placed inside the cavity. The temperature of the walls of the cavity and the cavity radiation is $T_1$ and $T_2 > T_1$. Both convection and radiation mechanisms are operative. The total heat energy lost by $P$ in unit time is given by the sum of the convective and radiative losses,

$$Q = Ah(T_2 - T_1) + \varepsilon\sigma A(T_2^4 - T_1^4). \quad (11)$$

As the object $P$ cools inside the cavity, its temperature $T_2$ reduces. If $c$ is the specific heat capacity and $m$ is the mass, the total heat lost by $P$ will be,

$$mc(T_2,\text{initial}) - mc(T_2,\text{final}) \quad (12)$$

and the rate at which the heat lost can be written as,

$$Q = -mc \frac{dT_2}{dt}, \quad (13)$$

where the minus sign shows heat being lost as temperature decreases. Comparing this with Equation (11), we obtain,

$$-mc \frac{dT_2}{dt} = Ah(T_2 - T_1) + \varepsilon\sigma A(T_2^4 - T_1^4). \quad (14)$$

and solving for the coefficient of convective heat loss,

$$h = \frac{-mc}{A} \frac{dT_2}{dt} - \varepsilon\sigma \frac{T_2^4 - T_1^4}{T_2 - T_1}. \quad (15)$$

This is a very important equation. Make sure you fully understand it and have re-worked the derivation. As $P$ cools, the temperatures $T_1$ and $T_2$ both change with time. Therefore, we can also write these temperatures as $T_1(t)$ and $T_2(t)$.
4 Apparatus

Our apparatus is an enhancement over the experimental setup described in [3].

1. Heating mechanism We have adopted two heating methods for the experiment. The first is a locally fabricated furnace (Adeel Electronics, Beden Road, Lahore) which is set at 220°C. It is fitted with a heating element and a probe-type thermocouple that automatically cuts off the electric supply when the temperature goes above the specified value.

You should be very careful and check for any current leakage using a tester before you touch it. Use thermal insulation gloves and the large tongs to transfer the cylinder into or out of the furnace.

The second method is the hot plate. The object to be heated is placed inside a bath of graphite powder on a hot plate. The hot plate reaches a maximum temperature of 400°C. Both heating options are depicted in Figure 4.

![Heating mechanisms for the experiment: (a) furnace and (b) hot plate.](image)

2. Cavity, Fan and Cylinder The cavity for our experiment has been fabricated locally (Noor Trading and Contracting Co., Rawalpindi) and adapted in-house. Both the walls of the cavity and the heated object (referred to hereafter as the cylinder) are made of mild steel oxidized at 800°C. The cavity has two inlets and is coated with a dull black paint inside for good radiative exchange (high value of emissivity $\varepsilon \approx 0.8-0.9$). Beneath the cavity, we have fitted an exhaust fan 12 V DC. 0.93 A (Pak Fans).

The cylinder (5 in. in diameter) can be placed in a mount with a cushion of alumina silicate, a good thermal insulator to minimize heat loss by conduction.

3. Lids: Perforated and Non-perforated We have used two kinds of lids in the experiment. The perforated lid is used in the first half of the experiment where our primary mode of heat loss is forced convection, with the fan switched on. The non-perforated lid is used in the second half of the experiment; it reduces the convective currents so that our primary source of heat loss becomes radiation.

4. Thermocouples The experiment employs two thermocouples (Farnell). One thermocouple is attached to a clamp that can tightly grip the heated cylinder. The second thermocouple is suspended in air, near the walls of the cavity.
5. Data Acquisition System  The experiment uses standard data acquisition hardware. The data acquisition (DAQ) card (National Instruments PCI-6221) acquires, digitizes and amplifies the thermocouple voltage signal. These signals are routed through the signal conditioning unit (National Instruments SCC-68). The unit also houses a thermistor for hardware-based cold junction compensation.

5  Experimental method

5.1  Newton’s law of cooling

Q 10. In the presence of forced convection, it is generally believed that the radiative losses are negligibly small as compared to convective losses. With this assumption, the radiative terms can be dropped out from (15),

\[ h = \frac{-(mc) \frac{dT}{dt}}{T_2 - T_1}. \]  \hspace{1cm} (16)

Furthermore, if we assume that \( T_1 = \)constant (as done conventionally), we can also replace \( \frac{dT_2}{dt} \) by \( \frac{dT_2 - T_1}{dt} \). We can make the substitution,

\[ T_2 - T_1 = x, \]  \hspace{1cm} (17)

and after some algebraic manipulation, the equation becomes,

\[ \frac{dx}{x} = -\frac{hA}{mc} \, dt. \]  \hspace{1cm} (18)

The solution is,

\[ x(t) = x_0 \exp(-hA t / mc). \]  \hspace{1cm} (19)

where \( x_0 \) is the initial value of \( T_2 - T_1 \).

Assume \( T_1 \) is constant at its average value, \( \langle T_1 \rangle \).
5.2 Experimental procedure

The schematic of the experimental setup is shown in Figure 6.

Figure 6: Schematic sketch of the experimental setup for demonstrating forced convection. Note the placement of the perforated lid.

★ Q 11. Measure the mass and surface area of the provided, black-coated and roughened mild steel cylinder. Note down your uncertainties.

★ Q 12. With the demonstrator’s help, place the cylinder inside steel box on the hot plate, fully cover it with the graphite powder and attach a thermocouple connected to the Digital Multimeter as to know the temperature of the cylinder being heated. Heat it to about 350°C.

★ Q 13. Now use the provided tongs and thermal gloves to carefully transfer the heated cylinder into the cavity. Never touch the surface of the cylinder, or the hot plate with your bare hands. These are extremely hot surfaces.

★ Q 14. In the meanwhile heat about 1500 ml water in a beaker to 80°C using hot plate.

★ Q 15. Open the Labview VI thermal.vi by double clicking the shortcut located on the Desktop. A front panel window with a grey background will open.

★ Q 16. Enter folder names where your data will be stored, for example C:\Documents and Settings\wasif.zia\Desktop\thermal1

★ Q 17. Enter the filenames for your data. You will make two files, one for the the cylinder e.m.f E2 and one for the cavity e.m.f T1. Therefore, your files could be named cylinder1 and cavity1. In this script, these files are also called the “data files”.

★ Q 18. Run the Labview file and use the data acquisition system to read the e.m.f values from the two thermocouples placed at room temperature. Also observe the table of e.m.f readings being built up. Ask your demonstrator for help if something is not clear.

★ Q 19. Now quickly follow the following steps, in the same order.
1. Attach the thermocouple marked \( E_1 \) inside the cavity.

2. Attach the thermocouple marked \( E_2 \) to the clamp, then clamp it onto the heated cylinder.

3. Place the perforated lid on the cavity.

4. Switch on the fan.

5. Run the VI by clicking the START button or by pressing CTRL+R.

★ **Q 20.** Carefully observe readings being picked by the Labview programme.

★ **Q 21.** Place a thermocouple connected to the GWInstek Digital Multimeter, labeled G inside the beaker. Switch the knob on the multimeter so as to display the temperature in °C. Place a different thermocouple labeled \( E_3 \) and connected to the DAQ in the beaker. Care should be taken that \( E_3 \) and G are properly dipped in the water, close to each other and on the same level inside the beaker, and should not touch beaker walls.

★ **Q 22.** Record the e.m.f generated by the \( E_3 \) and the temperature shown by G, then tabulate your results as given in Table (1).

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>e.m.f (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>.</td>
</tr>
<tr>
<td>75</td>
<td>.</td>
</tr>
<tr>
<td>70</td>
<td>.</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>45</td>
<td>.</td>
</tr>
</tbody>
</table>

Table 1: Sample format for calibration.

★ **Q 23.** Plot a graph using the Table (1). Care should be taken that the temperature vector is your y-axis variable. Now type the following command in which you will enter guess values of slope and intercept from your experimental data, also add your defined x and y-axis variables in the same sequence as mentioned above.

```matlab
>> lsqcurvefit(@heat, [slope intercept], x-axis variable, y-axis variable)
```

Fit the plot using resultant outcomes.

★ **Q 24.** Monitor the e.m.f generated till you get asymptotic values called \( E_{eq} \) on both the thermocouples. Note down these values.

★ **Q 25.** What does this condition represent? Has the transfer of heat ceased altogether?

You can now stop the Labview programme, switch off the fan and focus on your data instead.
5.3 Data analysis for forced convection

**Q 26.** Run MATLAB and change the path to the folder that contains your data files acquired from Labview.

**Q 27.** In the command window, type the command$^1$.

```matlab
>> forcedconvection
```

The m-file processes and filters your thermocouple measurements and generates the following vectors.

<table>
<thead>
<tr>
<th>E.m.f generated by $T_1$</th>
<th>E1</th>
</tr>
</thead>
<tbody>
<tr>
<td>E.m.f generated by $T_2$</td>
<td>E2</td>
</tr>
</tbody>
</table>

The time values for the temperature data, $t$ *time*

**Q 28.** Convert the e.m.f values to temperature using calibration results. (Hint: Type command $(T1 = E1.*slope \text{ value} + \text{intercept \text{ value}})$).

**Q 29.** From the data acquired, plot $T_2 - <T_1>$ versus time, where $T_2$ is the temperature of the cylinder and $<T_1>$ is the average room temperature.

**Q 30.** Fit the plot to the exponential function given in Equation (19), you need to type in which you will enter guess values of $x_0$ and gradient from your experimental data, also add your defined $x$ and $y$-axis variables in the same sequence as given.

```matlab
>> lsqcurvefit(@exponential, [x0 gradient], x-axis variable, y-axis variable)
```

Fit the plot using resultant outcomes.

Why are we justified in using Equation (19)?

Call the demonstrator at this point and ask him/her to check your graphs.

**Q 31.** Now use the available data and Equation (15) to calculate the coefficient of convective heat transfer $h$. Use $\varepsilon = 0.05$ and $c = 620 \text{ J kg}^{-1} \text{ K}^{-1}$.

**Q 32.** Estimate the uncertainty in $h$?

5.4 Simultaneous radiative and convective loses

In this last part of the experiment, we will seal the cavity, closing its base and covering it with the non-perforated lid at the top. The arrangement is depicted in Figure 7.

**Q 33.** Slide the bottom cover gently down to the base of the cavity. Heat the cylinder again, carefully place it inside the cavity and put the non-perforated lid

$^1$The file thermal.m should be in the same folder as the acquired data files.
on top so that convection is reduced. Your VI files should be labeled as cavity2 and cylinder2. Run the VI thermal.vi and leave it running till you reach asymptotic values.

![Diagram showing a schematic sketch of the experimental setup for simultaneous convective and radiative heat losses.]

Figure 7: Schematic sketch of the experimental setup for simultaneous convective and radiative heat losses.

★ Q 34. Once again, use the Matlab file thermal to generate the processed data. You will see numbers generated in 3 columns. The first column represents \( \frac{dT}{dt} \), the second represents \( T_1 \) and the third \( T_2 \). Use these and Equation (15) to compute the mean value of \( h \).

★ Q 35. Plot a graph of \( h \) and temperature difference \( (T2 - T1) \). Use \( \epsilon = 0.85 \) and \( c = 620 \text{ J kg}^{-1} \text{ K}^{-1} \).

6 Experience Questions

1. Why is a light bulb hotter than tube light?
2. Are they really photons that warm us when we put our hands close to a heater?
3. Can we build a thermometer that measures temperature using colour?
4. Are there any animals with thermal vision?
5. Can we make fire by concentrating sun rays with a lens made of ice?

7 Idea Experiments

1. As water is heated, the temperature does not rise linearly. Design an experiment to measure the rise in temperature with time and describe your results in terms of Newton’s cooling [4].
2. Measure the specific heat capacity of water through its cooling curve [5].
3. Is a white surface really a poor emitter of radiation? Compare the cooling curves of (a) an unpainted shiny metal, (b) a metal painted pitch black and (c) a metal painted white.
4. Find out about the wall construction of the cabins of large commercial airplanes, the range of ambient conditions under which they operate, typical heat transfer coefficients on the inner and outer surfaces of the wall, and the heat generations inside. Determine the size of the heating and air-conditioning system that will be able to maintain the cabin at 26° at all times for an airplane capable of carrying 400 people [1].

References


