Heat Transfer

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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, Labview file thermal.vi.

1 Labview file

Thermal.vi.

2 Conceptual Objectives

In this experiment, we will,

1. understand different modes of heat transfer,
2. identify the role of thermally conducting and insulating materials,
3. learn about temperature measurements using thermocouples,
4. corroborate experimental results with theoretical predictions, and mathematically model natural processes.

3 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.

4 Theoretical Introduction

4.1 Thermal conduction

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 Watts). 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. 1(a). We want to mathematically model this simple process 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,

$$Q_{cond} = -kA\frac{(T_2 - T_1)}{L}. \tag{1}$$

Sometimes, this equation is also written as,

$$q_{cond} = -k\frac{(T_2 - T_1)}{L}. \tag{2}$$

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

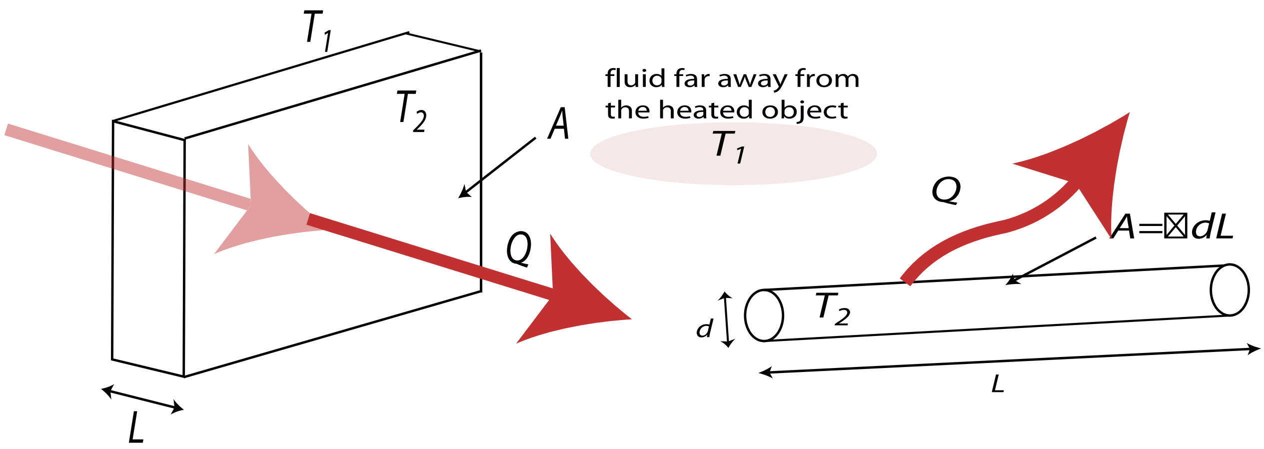


Figure 1: (a) Conductive transfer of heat from the hot to the cold end of a rod. The power transmitted is Q through an area A and across a length. (b) Setting for Newton's law of cooling. The power transmitted from a rod of surface area A is Q. The surface is at a steady temperature of T_2 and T_1 is the temperature of a mass of air far away.

Q 1. What are the SI units for the *conductivity*, 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 m^{-1} K^{-1}.

4.2 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.

4.3 Newton's law of cooling

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

$$Q_{conv} = hA\,(T_2 - T_1), \tag{3}$$

and in terms of power density,

$$q_{conv} = h\,(T_2 - T_1). \tag{4}$$

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_{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*.

Q 3. What are the units of h? How do these compare with the units of k?

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 empirically determined quantity.

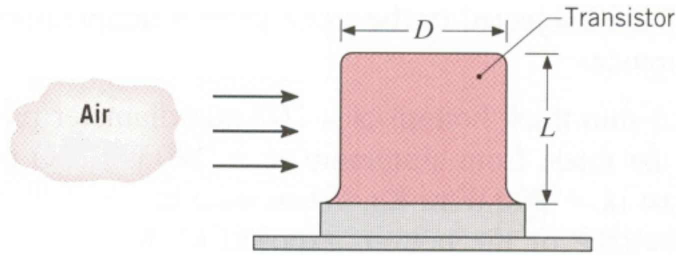
Q 4. Hot air at 80°C is blown over a 2×4 m^2 flat surface at 30°C. If the average coefficient of convective heat transfer is 55 W m^{-2} K^{-1}, determine the rate of heat transfer from the air to the plate [1].

4.4 Forced convection

Many electronic devices these days including computers are equipped 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 W m^{-2} K^{-1} 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 m^2, 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 extremely hot, it becomes increasingly difficult to dissipate this heat and hence most of us resort to the luxuries of forced convection. We must remember that the human body has also 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°. 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].)

4.5 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? 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. Conversely 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 absorbtion 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,

$$Q_{rad} = \sigma A T_2^4, \tag{5}$$

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

$$q_{rad} = \sigma T_2^4, \tag{6}$$

where σ is a constant with a value of 5.67×10^{-8} W m^{-2}K^{-1}, 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 power 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 ε, called the *emissivity*. Equation (8) is modified to,

$$q_{rad} = \varepsilon \sigma T_2^4. \tag{7}$$

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 B) that completely encloses the object of interest (call it A), as shown in Figure 2. The surface B emits at a lower temperature T_1, the output power density being,

$$q_{rad} = \varepsilon\sigma T_1^4. \tag{8}$$

The net power density being transferred from A to B becomes,

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

and the radiative power transmitted is,

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

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?

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

$$Q = Ah\,(T_2 - T_1) + \varepsilon\sigma A(T_2^4 - T_1^4). \tag{11}$$

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

$$mc(T_{2,initial} - T_{2,final}) \tag{12}$$

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

$$Q = -mc\,\frac{dT_2}{dt}, \tag{13}$$

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

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

and solving for the coefficient of convective heat loss,

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

Equation (14) is really important equation. Make sure you fully understand it and have re-worked the derivation. As A cools, the temperatures T_1 and T_2 both change with time. Therefore, we can also write these temperatures as $T_1(t)$ and $T_2(t)$.

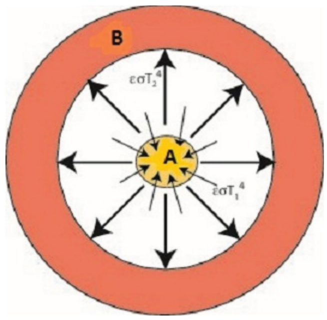
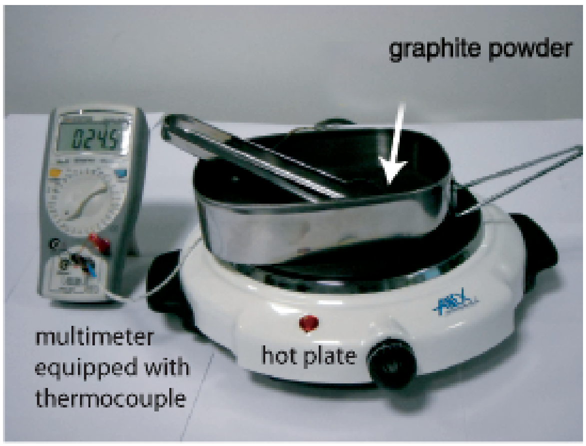


Figure 2: A blackbody A is placed inside another blackbody B. The long arrows emanating outwards from A represent the thermal power emitted by A and the short arrows pointing inwards represent the thermal power absorbed by A.

5 Apparatus

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

1. **Heating mechanism** We use a hot plate for heating our object. The object is placed inside a bath of graphite powder on a hot plate. The hot plate reaches a maximum temperature of 400^oC.



(b)

Figure 3: Heating on a hot plate.

2. **Cavity, Fan and Cylinder** The cavity for our experiment has been fabricated 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 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.

   The object which is shaped as a cylinder 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.

4. **Thermocouples** The experiment employs two thermocouples. 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.

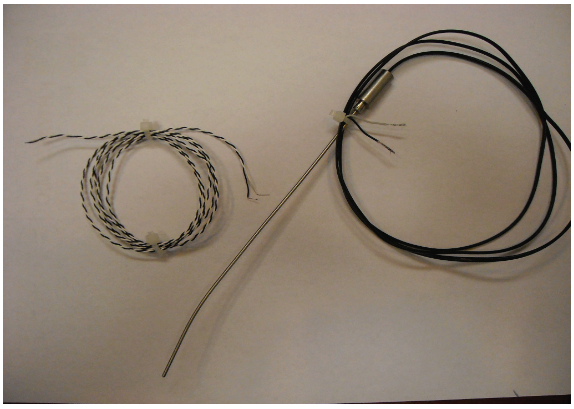


Figure 4: Thermocouples used in the experiment.

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.

6 Experimental method

6.1 Lumping convection and radiation into Newton's law of cooling

In the presence of convection, it is a reasonable assumption that the radiative losses are negligibly small as compared to convective losses so that these can be lumped together with the convection. With this assumption, the radiative terms can be dropped out from (15), and all kinds of losses can be lumped into the parameter h. This is called Newton's law of cooling.

$$h = \frac{-(\frac{mc}{A})\frac{dT_2}{dt}}{T_2 - T_1}. \tag{16}$$

Furthermore, if we assume that T_1 =constant, we can also replace dT_2/dt by $d(T_2 - T_1)/dt$. Finally if we make the substitution T_2-T_1=x, and after some algebraic manipulation, the equation becomes,

$$\frac{dx}{x} = -\frac{hA}{mc}\, dt, \tag{17}$$

whose solution is,

$$x(t) = x_0 \exp\left(-hA\,t/mc\right), \tag{18}$$

where x_0 is the initial value of $T_2 - T_1$. We assume that T_1 is constant at its average value, $\langle T_1 \rangle$.

6.2 Experimental procedure

The schematic of the experimental setups is shown in Figure 5.

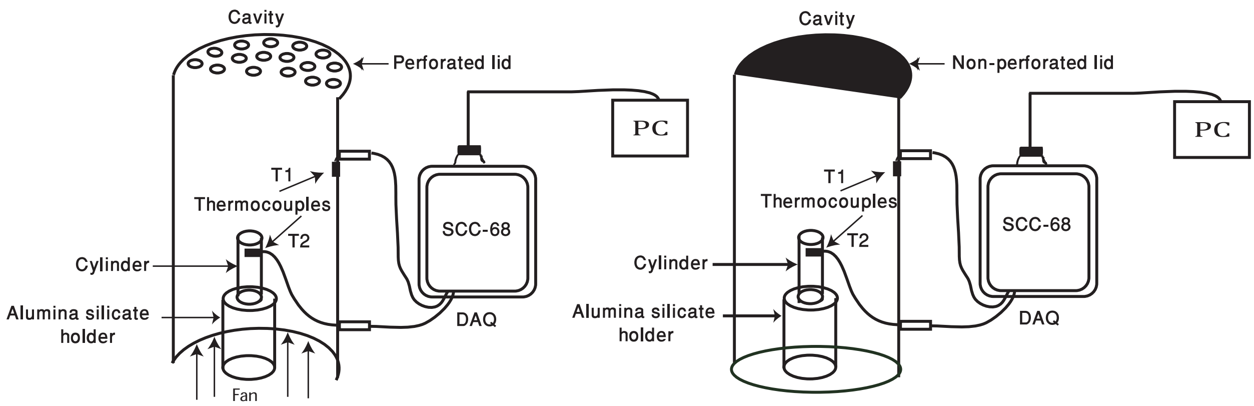


Figure 5: (a) Schematic sketch of the experimental setup for demonstrating forced convection. Note the placement of the perforated lid. (b) Schematic sketch of the experimental setup for simultaneous convective and radiative heat losses.

Q 10. Measure the mass and surface area of the provided, black-coated and roughened mild steel cylinder. Note down your uncertainties.

Q 11. 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 observing the temperature of the cylinder. Heat it to about 300°C.

Q 12. 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 13. Open the Labview VI **thermal.vi** by double clicking the shortcut located on the Desktop.

Q 14. Enter folder names where your data will be stored, for example
C:\Documents and Settings\wasif.zia\Desktop\thermal1

Q 15. The files you will create will have three columns, one for the time, one for the cavity temperature T_1, one for the cylinder temperature T_2. In this manuscript, these files are also called the "data files".

Q 16. Run the Labview file and use the data acquisition system to read the temperature values from the two thermocouples. Ask your demonstrator for help if something is not clear.

Q 17. Now quickly follow the following steps, in the same order.

1. Attach the thermocouple marked (T_1) inside the cavity.
2. Attach the thermocouple marked (T_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 18. Carefully observe readings being registered by the Labview programme.

Q 19. Monitor the temperatures generated till you get asymptotic values called T_{eq}, on both the thermocouples. Note down these values.

Q 20. 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.

Q 21. 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 23. Fit the plot to the exponential function given in Equation (18).

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

Q 24. Now use the fit estimate the coefficient of heat transfer h.

Q 25. You will now repeat the experiment with the solid lid and the fan switched off. Plot the cooling curve, fit and estimate h. Comment on how this condition compares with forced convection.

Q 26. Linearize both graphs and plot on the same scale.

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 20° at all times for an airplane capable of carrying 400 people [1].

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