How do objects heat and cool?
Comparing natural and forced convection

Umar Hassan, Mohsina Asif, Umm-e-Rubab, Iqra Aslam, Muhammad Rizwan, Azeem Iqbal, Kaneez Amna and Muhammad Sabieh Anwar

LUMS School of Science and Engineering

January 12, 2022
Version 2022-1

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 · Newton's Law of Cooling · Thermocouple · Data Acquisition · Duty Cycle

1 Conceptual Objectives

In this experiment, we will,

1. understand different modes of heat transfer notably forced and natural convection,
2. identify the role of thermally conducting and insulating materials,
3. learn about temperature measurements using thermocouple, and
4. corroborate experimental results with theoretical predictions, and mathematically model natural processes of heating and cooling of an object.

2 Experimental Objectives

In the present experiment, we heat a copper rod and observe how it cools with time and what factors affect the cooling rate. In one part, we allow the object to be cooled with the help of forced air currents by fan and in the other, fan is switched off. We will also learn how to use the thermocouple, an important component of numerous industrially important processes. We will also observe that heating an object does not instantaneously raise its temperature, rather it changes only gradually. We will also get familiar with the compound use of PhysWatt (CC/CV/CP Power Supply) and PhysLogger (Data Acquisition Device) that are home-built devices and are manufactured in PhysLab.

3 Theoretical Introduction

3.1 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.

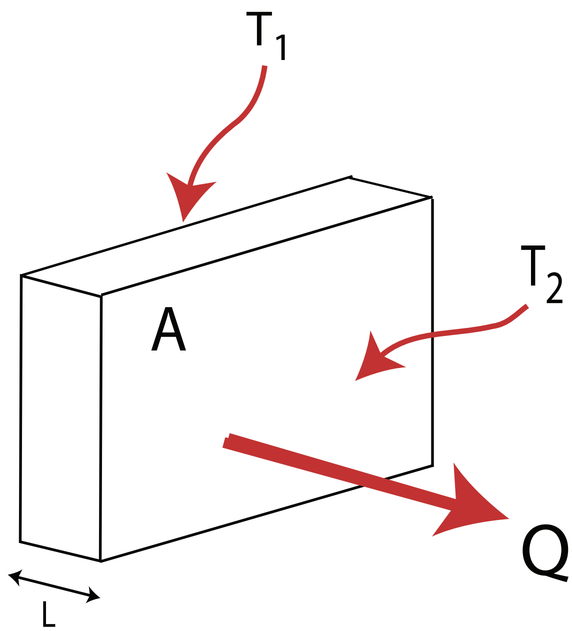


Figure 1: Conductive transfer of heat from the hot to the cold end of a rod. The power transmitted is Q through an area A and across a length L.

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 $m^{-1}K^{-1}$.

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,

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

and in terms of power density, i.e. energy transferred per unit surface area,

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

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].

3.4 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].)

Now suppose an object of surface area A is heated to a temperature T_2 and placed inside an environment of constant temperature T_1. We assure that both conduction and convection can be modeled through a coefficient of heat transfer h. The total heat energy lost by A in unit time is given by,

$$Q = Ah\,(T_2 - T_1). \tag{5}$$

As the object cools, its temperature T_2 reduces. If c is its specific heat capacity, the rate at which the heat lost can be written as,

$$Q = -mc\,\frac{dT_2}{dt}, \tag{6}$$

where the minus sign shows heat being lost as temperature decreases. Comparing this with Equation (5), we can write,

$$-mc\,\frac{dT_2}{dt} = Ah\,(T_2 - T_1), \tag{7}$$

and solving for the coefficient of convective heat loss,

$$h = \frac{-\left(\frac{mc}{A}\right)\frac{dT_2}{dt}}{T_2 - T_1}. \tag{8}$$

Equation (7) is a really important equation. Make sure you fully understand it and have re-worked the derivation. As the object cools, the temperatures, T_2 changes with time. Therefore, we will ask you to use Equation (8) and the experimental data to calculate h.

4 Overview

Our task is to observe,

1. How does copper rod change its temperature T because of the often simultaneous processes of natural and forced convection,

2. measuring the cooling curve of temperature T versus time t after heating, both with fan ON and OFF, and

3. applying Newton's law of cooling Equation (8), to estimate the coefficient of heat transfer h in air for each convection process.

5 Apparatus

Our apparatus is a modification over the experimental setup described in [3].

1. **Heating mechanism** We use two cartridge heaters rated at 40 W and 12 V embedded at the same location inside a copper rod which is further placed inside a perforated steel casing. A voltage of 8 V is supplied to each heater using channels A and B of the PhysWatt. Customized square waveforms are provided to heaters and the fan.

2. **Cavity, fan and cylinder** The cavity for our experiment has been fabricated in-house. It is a perforated steel cylinder that houses two cartridge heaters and a thermocouple. The perforations allow flow of air. The cylinder also acts as a heat sink. Above the cavity, we have fitted a standard DC power supply fan rated 12 V DC, 0.16 A.

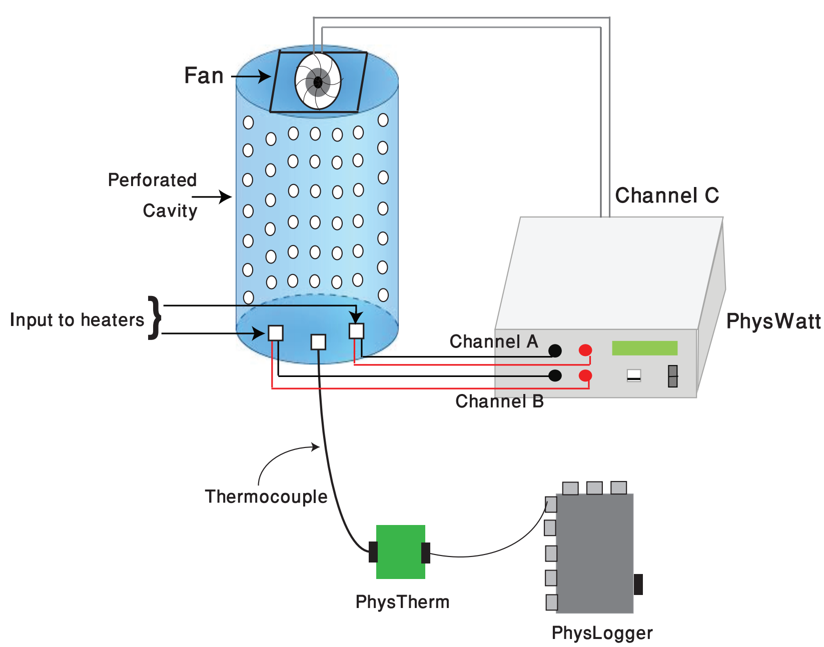


Figure 2: Schematic diagram of experiment for demonstrating Newton's law of cooling. This assembly is used for investigating heating and cooling dynamics.

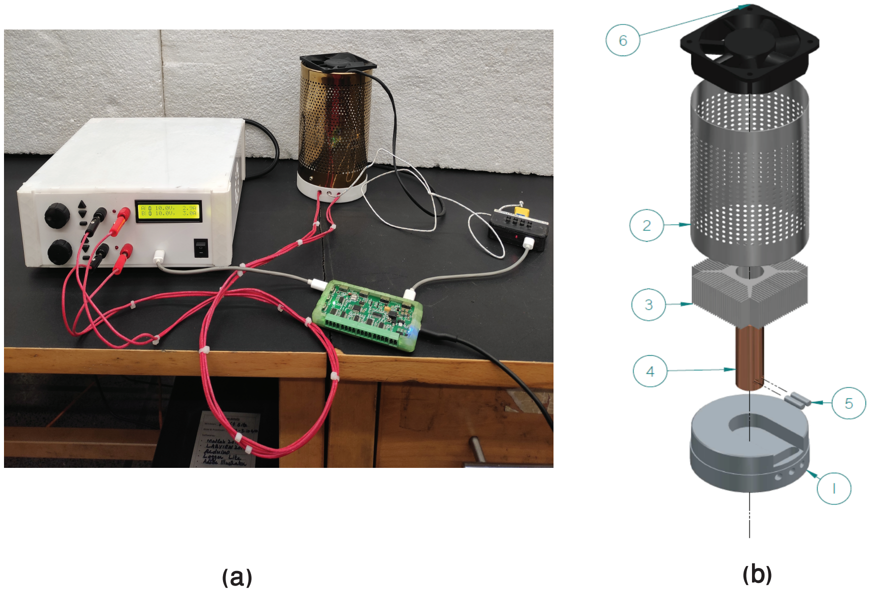


Figure 3: (a) A photograph of the experimental setup. (b) Exploded view of the perforated cylinder, showing (1) teflon base, (2) stainless Jar, (3) heat sink, (4) copper rod, (5) cartridge heater and (6) fan.

3. **PhysLogger—Data Acquisition System** The experiment uses a low-cost data acquisition device manufactured by PhysLab called "PhysLogger". It consists of 4 analog input channels that can be used to acquire differential voltage signals with sampling frequencies up to 20 kHz. The data is collected in time domain using the PhysLogger application installed on the computer.

4. **PhysTherm** Temperature is measured using a thermocouple. A *thermocouple* is employed in the experiment that is attached to the wall of the rod close to the heaters. The signal from the thermocouple is conditioned using an instrument that is our PhysTherm which records the change in temperature. Phystherm is further attached to the PhysLogger which routes the temperature to the PC and we can then observe and make educated guesses about it.

6 Experimental method

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

As mentioned earlier, 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. Here we reproduce Equation (8):

$$h = \frac{-\left(\frac{mc}{A}\right)\frac{dT_2}{dt}}{T_2 - T_1}. \tag{9}$$

which is also called Newton's law of cooling. 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 $T_2 - T_1 = x$, then upon some algebraic manipulation, the former Equation becomes,

$$\frac{dx}{x} = -\frac{hA}{mc}\,dt, \tag{10}$$

whose solution mimics the experimental decay curve,

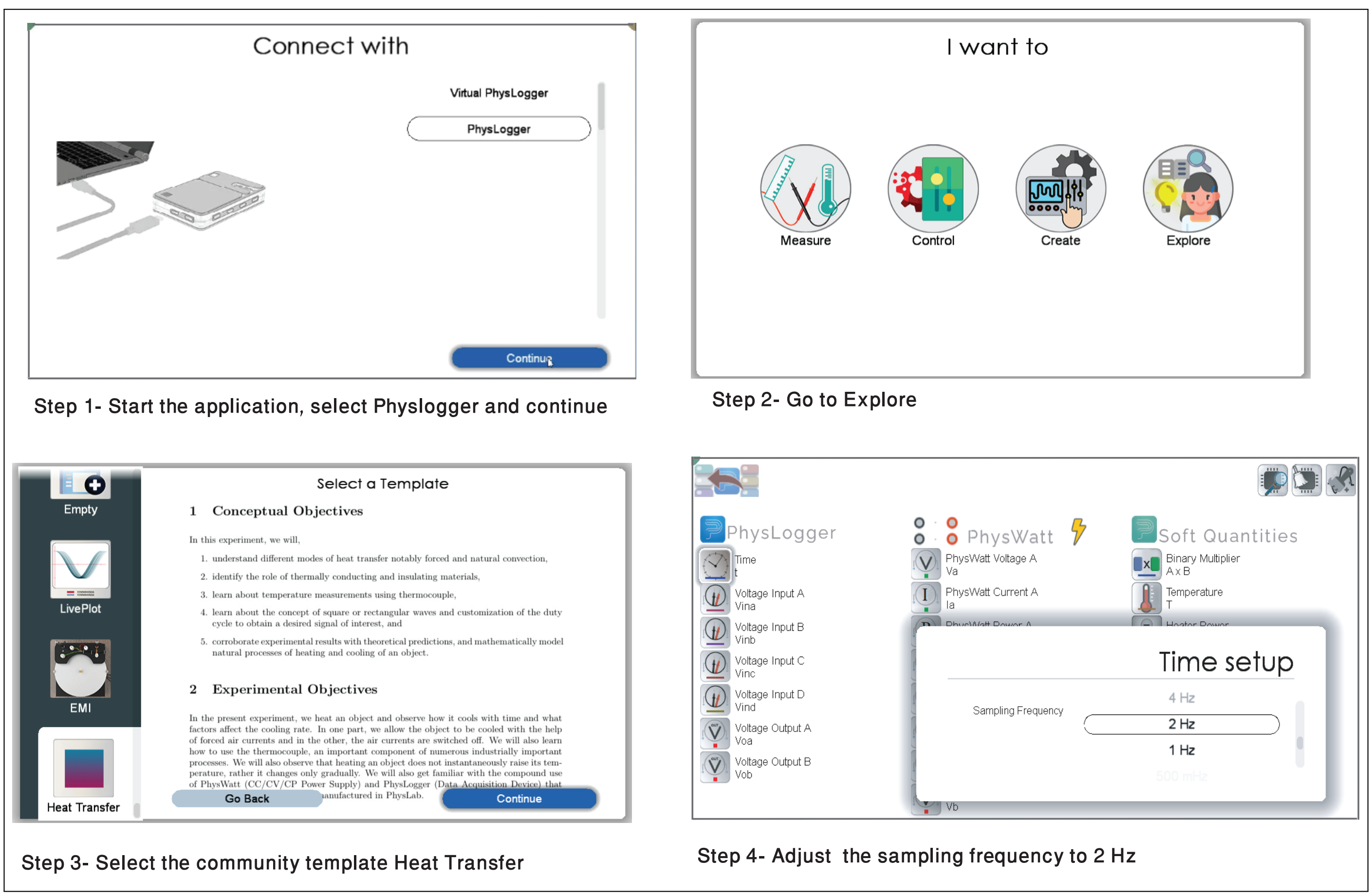
$$x(t) = x_0 \exp\left(-hA\,t/mc\right), \tag{11}$$

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

Make sure that the connections are made according to the schematic diagram shown in Figure 2(a). Channel A and B of PhysWatt are connected with the cartridge heaters while channel C of PhysWatt is connected to the fan. Also, connect PhysWatt with one of the digital channels (P_A, P_B, P_C,or P_D) of PhysLogger by inserting a USB-C cable. Connect the PhysTherm with one of the analog channels of the PhysLogger and finally, also connect the PhysLogger to the PC.

Pictorial procedure



Step 1- Start the application, select Physlogger and continue

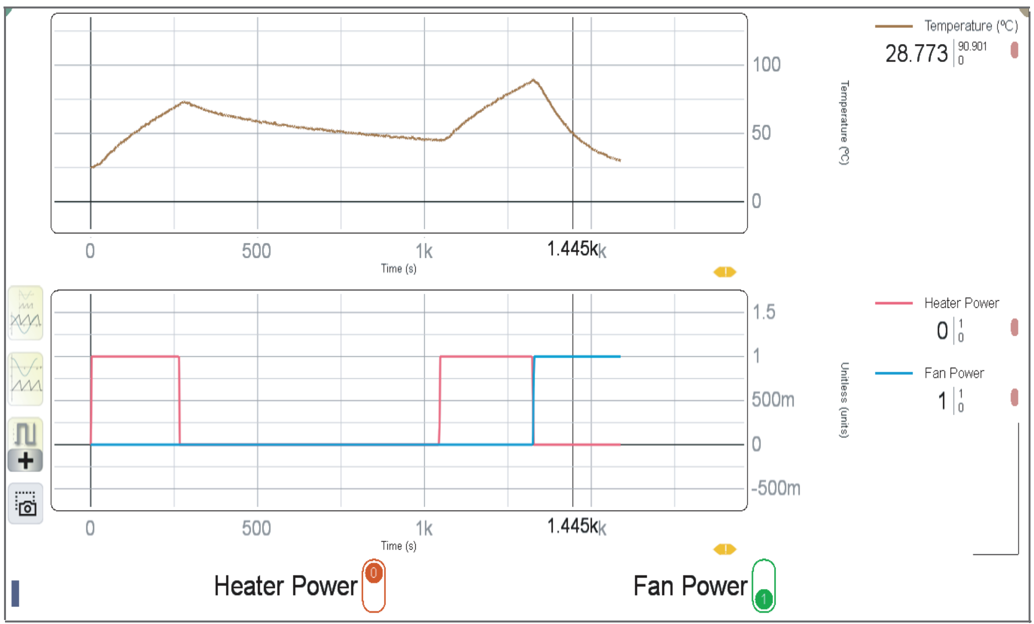
Step 2- Go to Explore

Step 3- Select the community template Heat Transfer

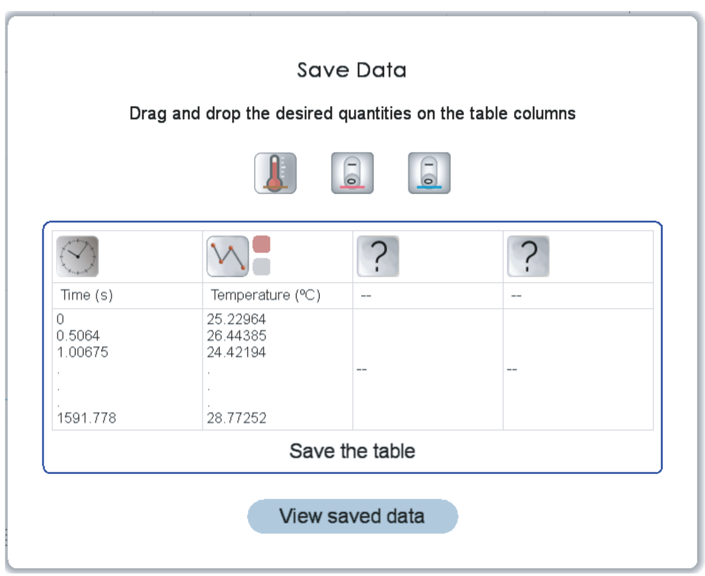
Step 4- Adjust the sampling frequency to 2 Hz

Before you start the experiment, ensure that the default save location for all data and screenshots is set to a directory you have access to. This location can be changed by clicking on `Options > Preferences`.

Caution: After turning the heater ON, never touch the surface of the perforated cylinder with bare hands. These are extremely hot surfaces.



Step 5- If needed, clear the previous data using the button. Turn the heater ON for 4 to 5 mins. A live plot will show on th Physlogger interface. Now turn the heater OFF and allow perforated cylinder to cool natuarlly. Again turn the heater ON for same time period. After switching OFF the heater, ON the fan placed inside the perforated cylinder casing. Cooling with fan on mimics forced convection. Recorded data will show on the Physlogger interface



Step 6- Export the data using the save option. Quantities need to be dragged and dropped on the respective table's columns before you click on Save the table

6.3 Investigate further

The saved data (time vs temperature) can be easily imported to MATLAB and any other software for further processing. You are required to come up with suitable graphs and respond to the following points of inquiry.

1. Plot temperature versus time graph for each condition. What does natural and forced convection represent? Has the transfer of heat ceased altogether or does it take time?

2. Plot log $(T_2 - T_1)$ on the y-axis and time on the x-axis where T_2 is the temperature recorded while T_1 is the average ambient temperature. Determine the value of slope and the intercept using weighted fit of a straight line.

3. You are provided with the mechanical drawing of copper rod, measure its mass and the surface area. Estimate the coefficient of heat transfer h for each convection. Comment on how value of h for both conditions can be compared with each other. Note down your uncertainties.

4. Fit the plot to the exponential function given in Equation (11). Linearize both graphs and plot on the same scale.

5. Comment on how the object heats up. Is the temperature rise instantaneous or gradual? What mathematical equation can describe the heating process? Solve this equation and see if your heating profile matches the solution.

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].

References

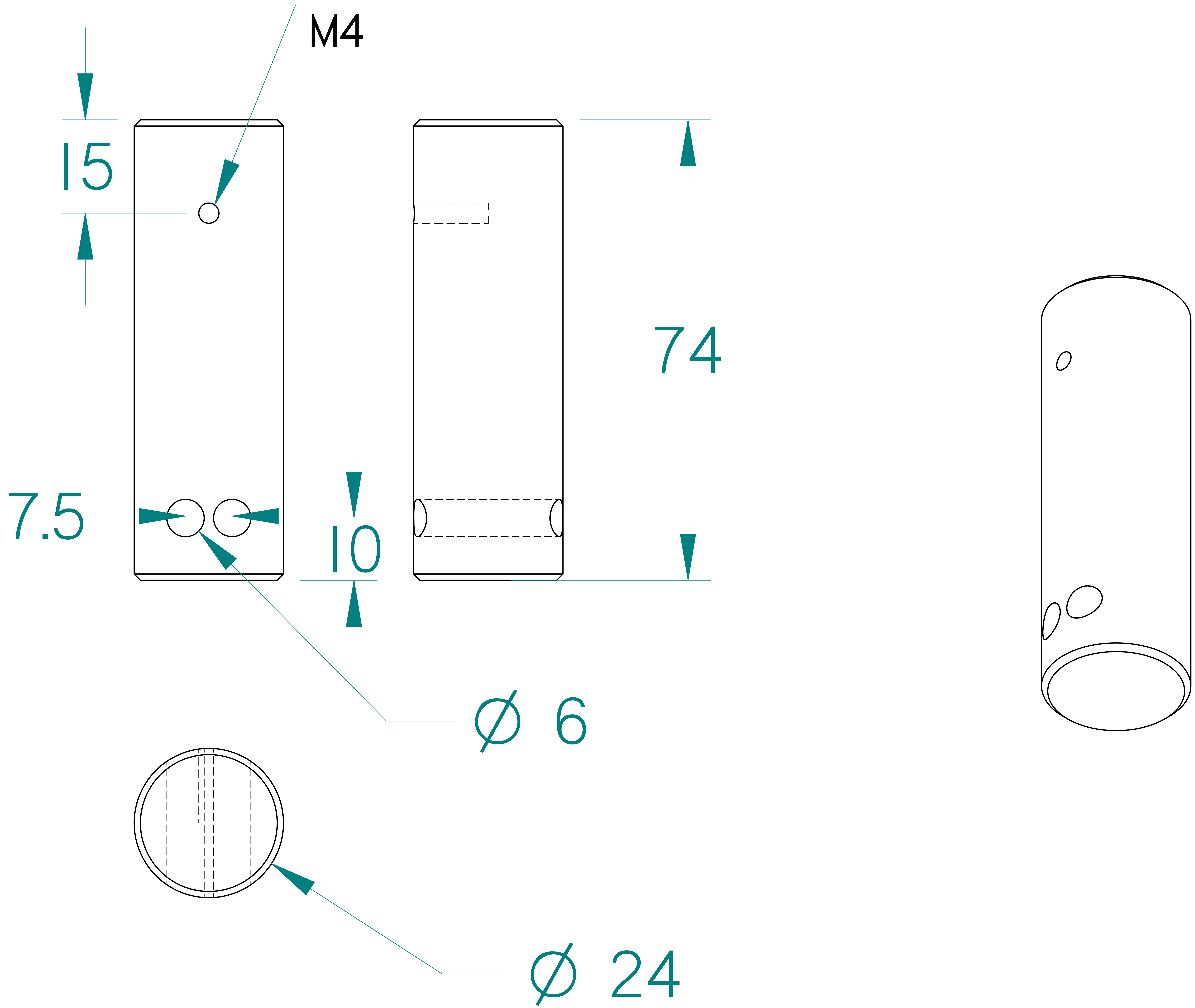
[1] Y. A. Çengel, R. H. Truner, Fundamentals of Thermal-Fluid Sciences, (McGraw Hill, 2001).

[2] F. P. Incropera, D. P. DeWitt, Fundamentals of Heat and Mass Transfer, (Wiley & Sons.), pp. 1-47.

[3] J.E. Spuller, R. W. Cobb, "Cooling of a vertcal cylinder by natural convention: an undergraduate experiment", Am. J. Phys. **61**, 568 (1993).

[4] J. O'Connell, "Heating water: rate correction due to Newtonian cooling", Phys. Teacher **37**, 551 (1999).

[5] C. R. Mattos, A. Gaspar, "Introducing specific heat through cooling curves", Phys. Teacher **40**, 415 (2002).



SIZE A4	Copper Rod	Unit mm
FILE NAME: Copper Rod.dft		
SCALE: 3.1	Date:10/01/2022	
MATERIAL: Copper Rod		