

# How do objects heat and cool?

## Comparing natural and forced convection

Umar Hassan, Mohsina Asif, Umm-e-Rubab, Iqra Aslam,  
Muhammad Rizwan, Azeem Iqbal, and Muhammad Sabieh Anwar  
LUMS School of Science and Engineering

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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 · 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,
4. learn about the concept of square or rectangular waves and customization of the duty cycle to obtain a desired signal of interest, and
5. 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 an object 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 and in the other, the air currents are 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,

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

Sometimes, this equation is also written as,

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

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

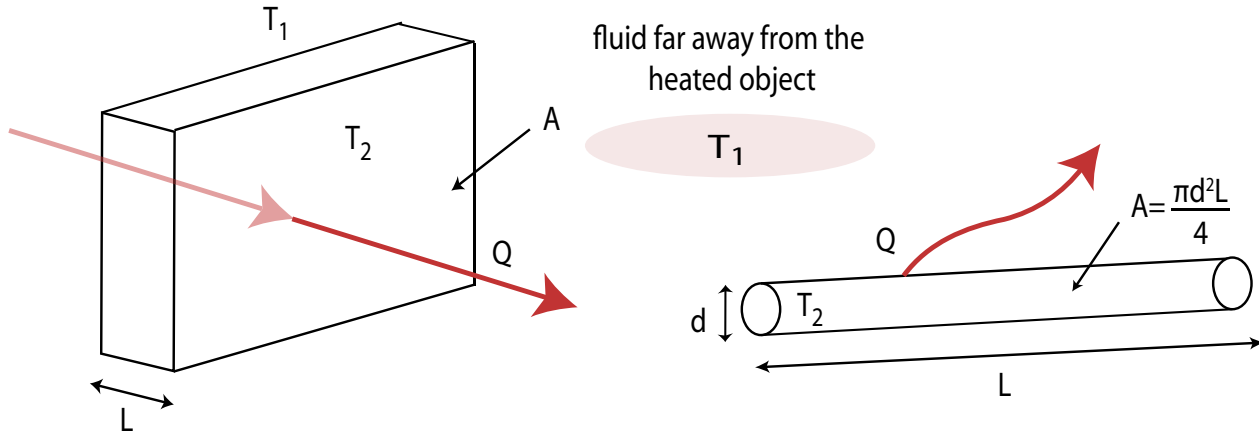


Figure 1: (a) Conductive transfer of heat from the hot to the cold end of a rod. The power transmitted is  $Q$  through an area  $A$  and across a length. (b) Setting for Newton's law of cooling. The power transmitted from a rod of surface area  $A$  is  $Q$ . The surface is at a steady temperature of  $T_2$  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  $25\text{ }^\circ\text{C}$  and  $40\text{ }^\circ\text{C}$ . 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  $1.4\text{ W m}^{-1}\text{K}^{-1}$ .

### 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,

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

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

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

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  $80^\circ\text{C}$  is blown over a  $2 \times 4 \text{ m}^2$  flat surface at  $30^\circ\text{C}$ . If the average coefficient of convective heat transfer is  $55 \text{ W m}^{-2} \text{ K}^{-1}$ , 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  $2\text{--}25 \text{ W m}^{-2} \text{ K}^{-1}$  whereas this could go as high up to  $250 \text{ W m}^{-2} \text{ K}^{-1}$  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  $90 \text{ W}$  per person and this heat must be dissipated. For an average human surface area of  $2 \text{ m}^2$ , the flux of heat that must be transferred to the atmosphere is  $45 \text{ W m}^{-2}$ . 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  $100 \text{ W m}^{-2} \text{ K}^{-1}$ . The temperature of the air is  $25 \text{ }^\circ\text{C}$  and the maximum temperature the transistor can withstand is  $60 \text{ }^\circ$ . The diameter and length are  $10 \text{ mm}$  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  $60 \text{ km h}^{-1}$ . The outside air temperature is  $5 \text{ }^\circ\text{C}$  and the air velocity results in a value of  $h \approx 50 \text{ W m}^{-2} \text{ K}^{-1}$ . The skin temperature is  $34 \text{ }^\circ\text{C}$ , 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,

$$Q = Ah(T_2 - T_1). \quad (5)$$

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,

$$Q = -mc \frac{dT_2}{dt}, \quad (6)$$

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

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

and solving for the coefficient of convective heat loss,

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

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 Apparatus

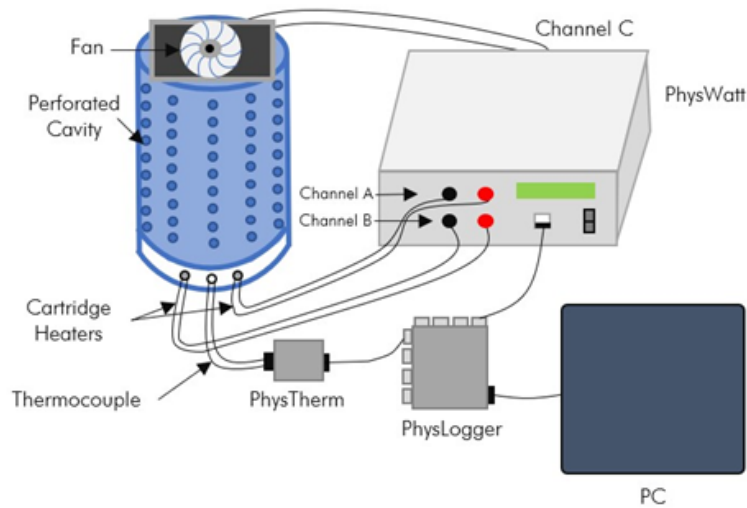
Our apparatus is a modification over the experimental setup described in [3].

1. **Heating mechanism** We use two cartridge heaters rated at  $40 \text{ W}$ ,  $12 \text{ V}$  embedded at the same location inside a copper rod which is further placed inside a perforated steel

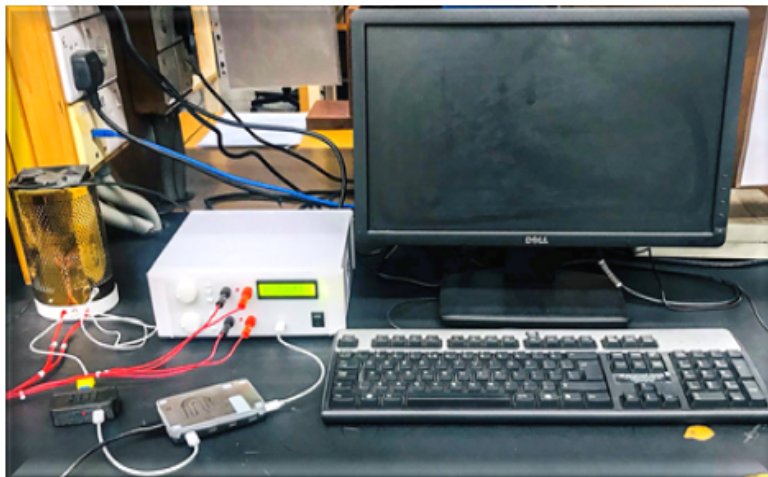
casing. To obtain the desired temperature, two heaters of the same rating are required that will certainly produce more heat collectively i.e., 80 W. Voltage of 8 V is supplied to each heater using channel A and B of the PhysWatt. Customized square waveforms are provided to heaters and the fan. These waveforms will automatically control the switching of fan when the desired heating time is over.

**Q 7.** Calculate the power that is being supplied to the heaters at this operating voltage at the duty cycle of, say, 25%.

- 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.



(a)



(b)

Figure 2: (a) Schematic diagram of experiment for demonstrating Newton's law of cooling. This assembly is used for investigating heating and cooling dynamics. (b) A photograph of the experimental setup.

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 the time domain using the PhysLogger application installed on the computer.
4. **PhysTherm** Since one *thermocouple* is employed in the experiment that is attached to the wall of the rod close to the heaters, hence a PhysTherm is connected with a thermocouple for recording the change in temperature which is further attached to the PhysLogger for data acquisition.

#### 4.1 Square/Rectangle wave and the duty cycle

In the heating operation, we apply a square pulse to the two heaters and a fan placed inside the perforated cylindrical casing. The duty cycle is the ratio of the time a circuit is kept ON to the time the circuit is kept OFF. It is expressed as a percentage of time a circuit is kept ON. For example, a duty cycle of 70% symbolizes that the pulse will be ON 70% of the time and OFF for the other 30%, ultimately providing us a rectangular wave. Similarly, if the duty cycle is 50%, the resultant wave is a square wave.

For the fan, the total time period of the waveform is 2500 s. If we set the duty cycle to 50%, it results in a square wave which will be high for 1250 s and low for 1250 s as illustrated in Figure 3 (a). For the heater, the total time period of the waveform is 1000 s. Therefore, if we set the duty cycle to 25%, it results in a rectangle wave which will be heating the heater for 250 s and will be low for the other 750 s as shown in Figure 3 (b).

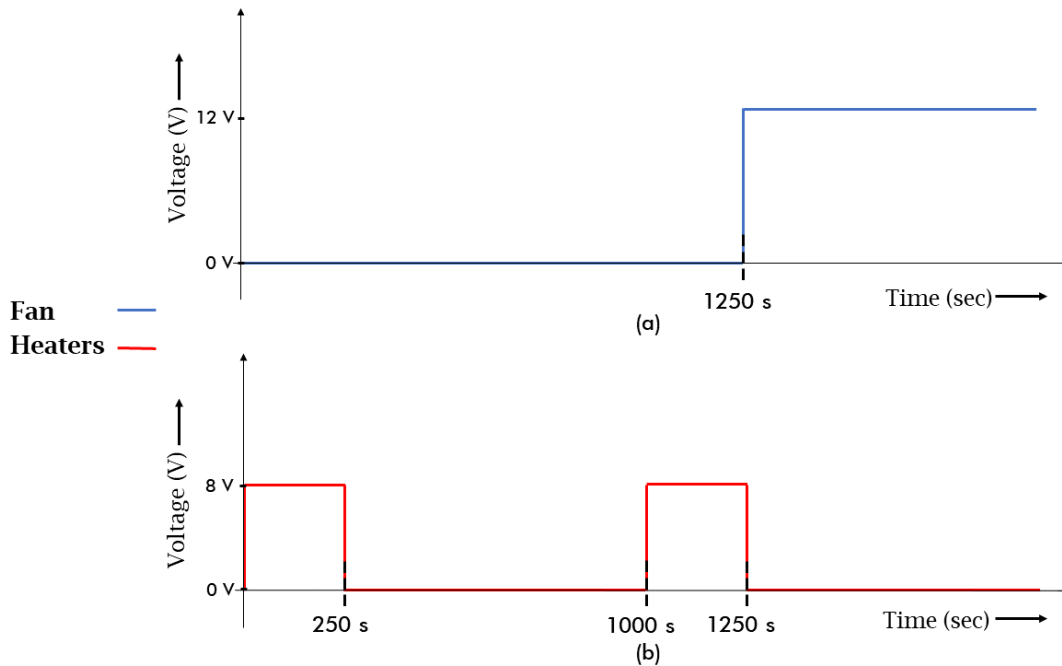


Figure 3: Voltage of varying duty cycle (a) supplied to fan, (b) and heater.

## 5 Experimental method

### 5.1 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):

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

which is also called Newton's law of cooling. If we assume that  $T_1 = \text{constant}$ , 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,

$$\frac{dx}{x} = -\frac{hA}{mc} dt, \quad (10)$$

whose solution is the experimental decay,

$$x(t) = x_0 \exp(-hAt/mc), \quad (11)$$

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

### 5.2 Experimental procedure

The perforated cavity includes two cartridge heaters of 40 W and 12 V with one thermocouple connected close to the heaters for temperature sensing.

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

1. 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 ( $P_A, P_B, P_C, P_D$ ) 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.
2. In the PhysLogger application, select 'PhysLogger' and continue. To record the measured temperature, click on **Measure > Temperature**. Set the input temperature range ( [ -260 °C, 200 °C ] < 1 °C resolution) for the channel to which your PhysTherm is connected.



3. After configuring temperature, Proceed to the workspace of the PhysLogger Desktop app. A live plot should appear on the screen.
4. Once on the workspace, go to Widgets to generate two square waves for heaters and the fan.

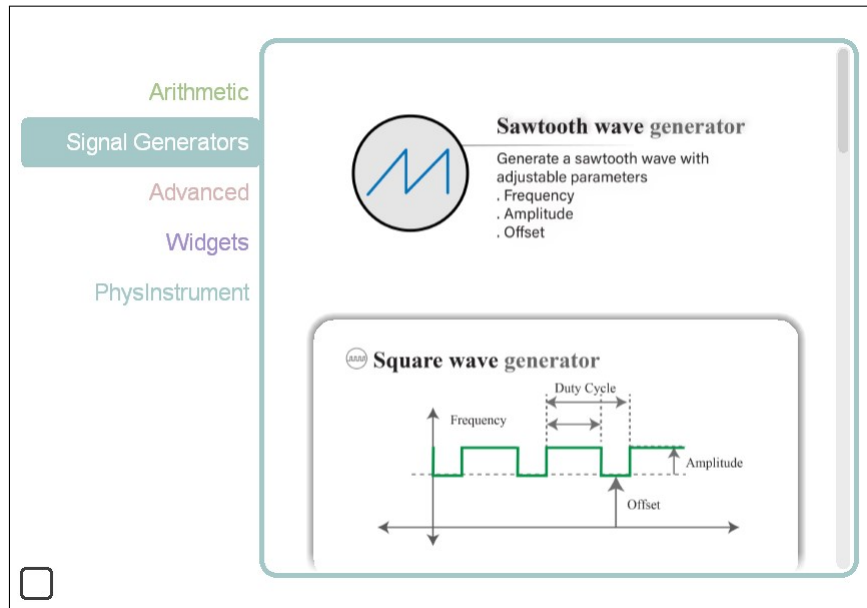


Figure 4: Generation of the square waves.

- To provide a square wave to heaters, set the amplitude to 8 V, frequency to 0.001 Hz, and duty cycle to 25%.

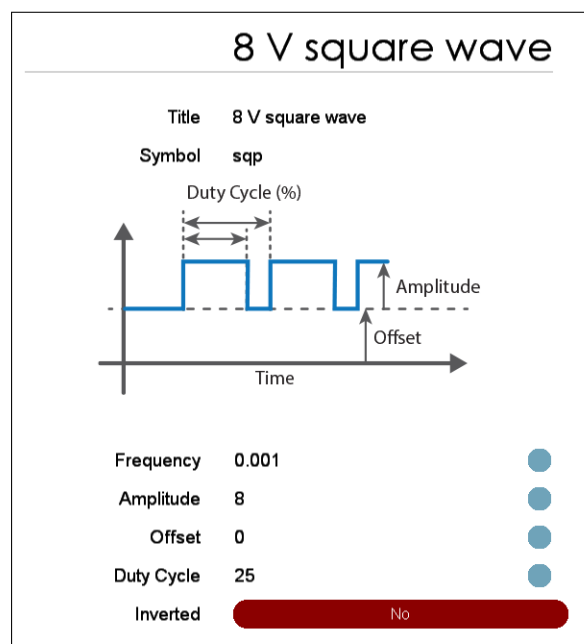


Figure 5: Customization of the square wave for the heaters.

- To provide an inverted square wave to the fan, adjust the amplitude 12 V, frequency 0.0004 Hz, duty cycle 50%, and click ‘Yes’ on inversion.

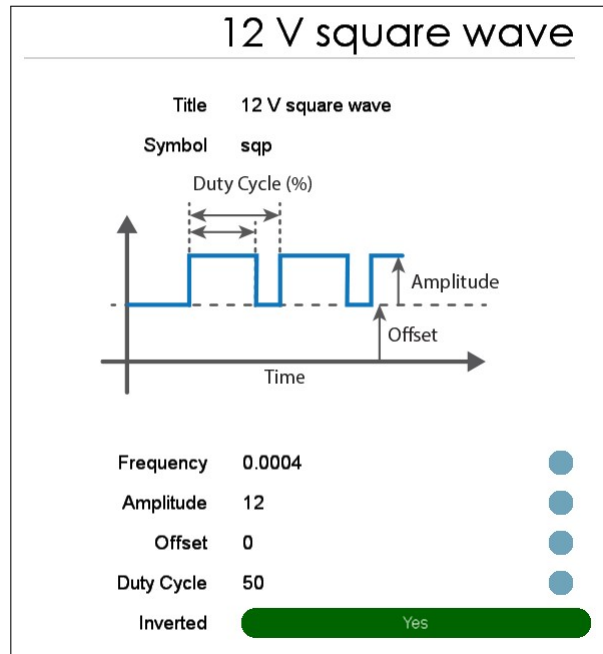


Figure 6: Customization of the square wave for the fan.

5. Click ‘Time’ and choose a sampling rate of 5 Hz.
6. In the App, modify the PhysWatt channel outputs. Set the voltages of Channels A and B of the PhysWatt to the 8 V square wave (generated in Step 4). Also, set the current limit of both channels to 3.5 A as illustrated in Figure 7.

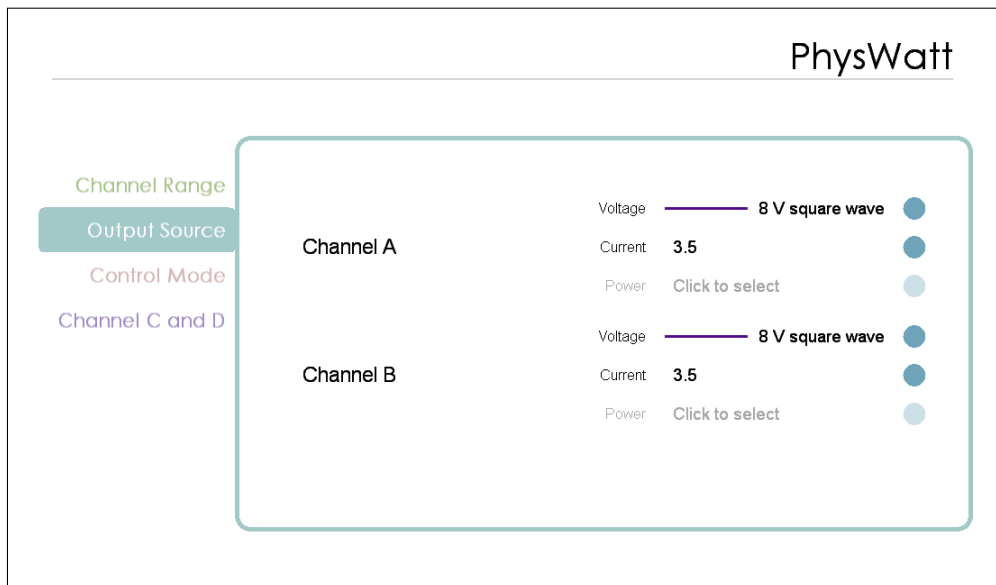


Figure 7: Supplying the square waves to Channel A and B of PhysWatt.

- Likewise, set the voltage of channel C of PhysWatt to the square wave of 12 V (generated in Step 4).

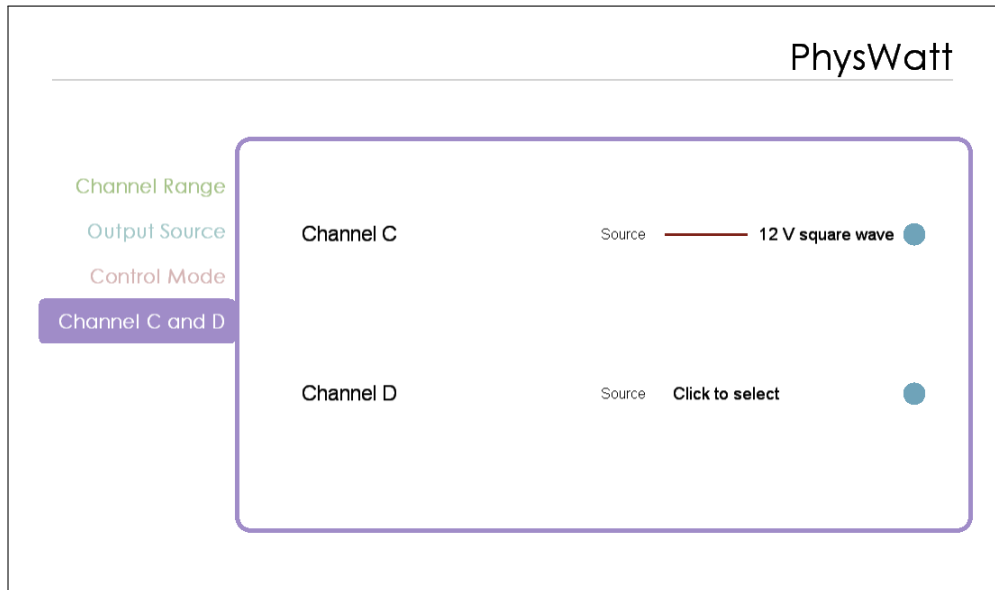


Figure 8: Supplying the square wave to Channel C of PhysWatt.

- (Optional) From the toolbar, open a new tab and plot a live graph of voltage with time for the affirmation of generation of the square wave for all channels.
- After getting the desired plot, 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).

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

**Q 8.** What does natural and forced convection represent? Has the transfer of heat ceased altogether or does it take time?

**Q 9.** From the data acquired, plot temperature versus time graph for each condition.

**Q 10.** 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. Fit the plot to the exponential function given in Equation (11).

**Q 11.** Use the curve fit to estimate the rate of heat transfer  $hA/mc$  for each convection. What are their units?

**Q 12.** Comment on how both conditions can be compared with each other.

**Q 13.** Linearize both graphs and plot on the same scale.

**Q 14.** 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.

## 6 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  $20^\circ$  at all times for an airplane capable of carrying 400 people [1].

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