Investigating Gas Laws and Heat Engine Cycles with PhysLogger

Mohsina Asif, Umar Hassan, and Muhammad Sabieh Anwar

May 21, 2022

1. Introduction

In this experiment, PhysLogger together with its compatible sensing instruments (called PhysInstruments) will be used to verify ideal gas laws, that are the Amonton's, Boyle's, and Charle's laws and investigate engine cycles.

Three sensing PhysInstruments: PhysBar, PhysDisp, and PhysTherm that measure pressure, distance, and temperature, respectively, are connected to PhysLogger, a datalogging and control device. PhysLogger acquires, plots, and records the aforementioned quantities that can be further manipulated. Some widgets in the PhysLogger Desktop App are also utilized in this experiment, as will be described in the procedure. Further details of the experiment can be found at: https://physlab.org/experiment/verifying_gas_laws/.

2. Figure of the Apparatus

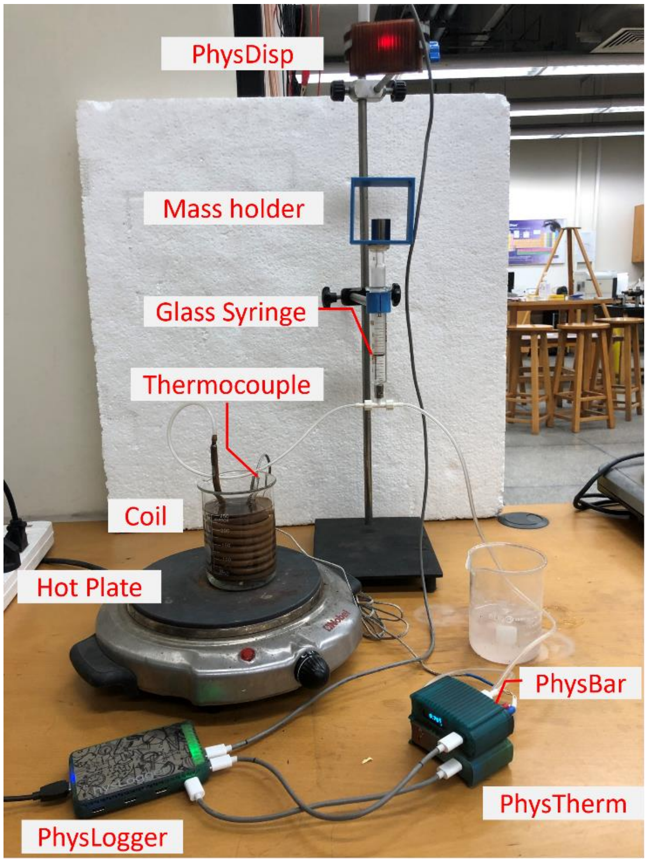


Figure 1: The experimental apparatus of the heat engine experiment. A thermocouple immersed in the water bath is inserted into the screw terminal block of PhysTherm. PhysTherm is connected to an analog channel of PhysLogger.

A tubing connects the air-tight hollow copper coil to the glass syringe. PhysBar is connected to the glass syringe with tubing and is connected to a digital channel of PhysLogger. PhysDisp is mounted vertically on top of the syringe. PhysDisp detects the distance moved by the plunger in a contact less manner. Ensure that the emitter and sensor of the TOF sensor of PhysDisp faces the top of the syringe. PhysDisp is also connected to a digital channel of PhysLogger. PhysLogger is connected to a PC via a USB cable.

3. Apparatus Details

See Section 3 for a visual representation of the apparatus. The details of the components are given below.

1. **Glass syringe**
   A 20 ml glass syringe will be used in this experiment. A glass syringe (instead of the more commonly available plastic syringe) is used due to its considerably lower friction.
   Note: These syringes are very fragile, and the plunger often tends to slip due to low friction. Handle these with utmost care and avoid turning the syringe upside down.

2. **Copper Coil** (hollow from inside to contain air molecules)
   Here, a copper coil is equivalent to an airtight flask. The good conductivity of copper and narrow diameter of the coil means the air inside the coils can be rapidly heated and cooled such that, at any given moment, every air molecule within the coil is assumed to be almost at the same temperature and the temperature of the water bath is assumed equal to the air inside the coil. Increasing the turns of the coil would increase the volume of air in our system.

3. **Plastic Tubing and Luer connectors**
   Components in this system are connected together using plastic tubing. Of course, to observe more pronounced effects, it is recommended to increase the length of the tubing as that will increase the volume of air inside our system. At junctions, we use Luer connectors.

4. **Beaker and Hot plate**
   A hot plate is used to heat the beaker which contains the copper coil immersed in water. (Alternatively, instead of a hot plate a hot air gun can also be used).

5. **PhysLogger**
   PhysLogger together with its Desktop App makes data logging quick, intuitive, and vivid. Further details about PhysLogger can be found at [1] and [2].

6. **PhysTherm and K-type thermocouple**
   The measured temperature readings by the thermocouple are fed to PhysTherm. PhysTherm amplifies and applies cold junction compensation to these signals that are then plotted as temperature readings in PhysLogger Desktop App. Thermocouple is connected

to PhysTherm with a **screw terminal connector** and PhysTherm is connected to an analog channel of PhysLogger with a USB C to C type cable.

7. **PhysDisp**
   PhysDisp is a displacement sensor that, in a contactless manner, measures the distance moved by the plunger of the syringe as gas in the syringe expands or compresses. Ensure that the emitter and sensor of the TOF sensor of PhysDisp faces the top of the syringe. These displacement readings that are logged by PhysLogger can be manipulated in the PhysLogger Desktop App to calculate volume of the gas in syringe. PhysDisp connects to a digital channel of PhysLogger.

8. **PhysBar**
   PhysBar measures the gas pressure inside the syringe. A nylon tubing can be inserted to the Luer socket on the PhysBar via a Luer connector. Ensure that there are no leakages in the connections. PhysBar is further connected to one of the digital channels of PhysLogger with a C type cable.

9. **Masses**
   Masses are placed and lifted on the system to increase and decrease the pressure of the system, respectively. This increases and decreases pressure on the syringe and will be especially used during the heat engine part of the experiment.

4. Measuring the Required Quantities

In this experiment, when investigating various gas laws and ultimately building a heat engine, a combination of **the following three basic quantities is usually measured:**

Quantity	Relevant PhysIntrument
• Temperature	PhysTherm
• Pressure	PhysBar
• Volume	PhysDisp

Plotting quantities against Time: The general procedure is to connect the relevant PhysInstruments to PhysLogger and go to `Measure` > (The quantity one needs to measure) > `Make a LivePlot Now` > `Save > Show in Explorer.` (To set a desired sampling frequency for your measurements, e.g., lower than 5 Hz, go to `Quantities Panel > Time.`)

Having quantities of your choice on the axes of LivePlots:
In addition to the fundamental LivePlots of these quantities against time, you can plot any combination of quantity against each other as well. For example, one may plot Volume against Temperature, to directly investigate Charles's Law in the App.

Custom LivePlots can be made by `Extensions > Build From Scratch > Widgets > LivePlots` > dragging and dropping the desired quantities on to the axis of this plot.

Remember! PhysBar and PhysDisp are **Digital PhysIntruments** and are not hot pluggable. This means, you need to connect these instruments to PhysLogger before starting the App in order to see `Measure > Pressure` and `Measure > Distance` in the App start page.

4.1. Measuring Temperature

PhysTherm together with K Type Thermocouple is used to measure temperature (as described in the previous section). You need to `Measure > Temperature.`

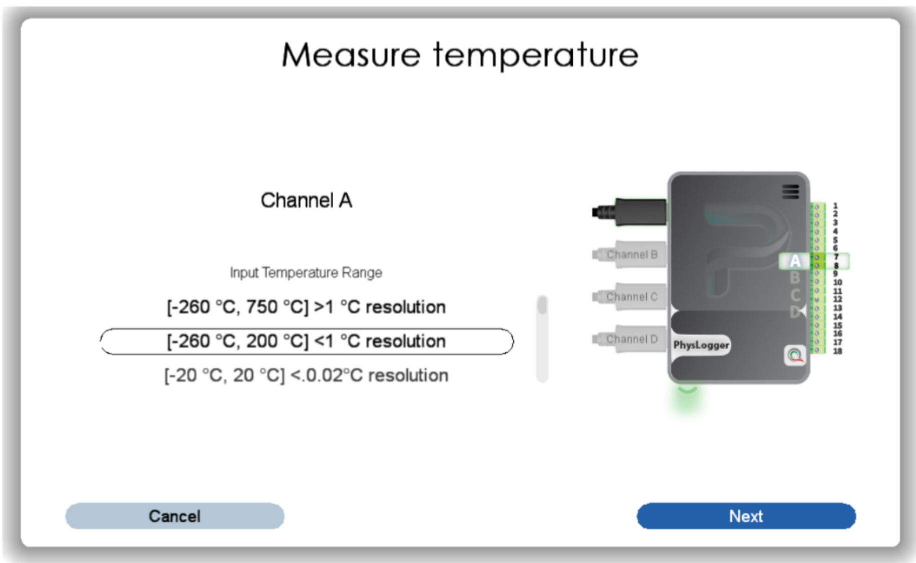


Figure 2: PhysTherm is connected to one of the analog channels of PhysLogger (in this case `Channel A`). Temperature is plotted by in the PhysLogger Desktop App.

For PhysTherm, it is recommended to set a thermocouple range of -260ºC to 200ºC (higher the range, greater the noise in our readings).

4.2. Measuring Pressure

Pressure is measured using PhysBar. Once PhysBar is connected to a digital channel of PhysLogger, when you launch the PhysLogger Desktop App, select `Measure > Pressure.`

Figure 3: If PhysBar is configured with PhysLogger, you can find the Pressure quantity in `Quantities Panel`, clicking on that quantity opens this.

4.3. Measuring Volume

We do not directly measure the changes in the volume of our glass syringe, but instead measure how much distance the plunger moves and use this distance and the diameter of our glass syringe to calculate the volume. This distance is measured with the PhysDisp.

Conveniently, this quick calculation can be done in the PhysLogger Desktop right away.

1. Ensure that PhysDisp is correctly mounted vertically above the glass syringe and connected to PhysLogger.
2. In the PhysLogger Desktop App, select `Measure > Distance`

Figure 4: When PhysDisp is connected correctly to PhysLogger, select `Measure > Distance` along with any other quantity that you need to measure (e.g., pressure, temperature, etc) `> Make a LivePlot now`. We can compute these displacement values to get the change in volume.

3. Tare (zero) the displacement readings when the plunger is at its minimum position, i.e., the syringe is closed. This can be done by navigating to Quantities Panel > Displacement > Tare. Alternatively, you can tare the displacement readings with the hardware button on your PhysDisp. Immediately, you will see the readings on your LivePlot become 0.

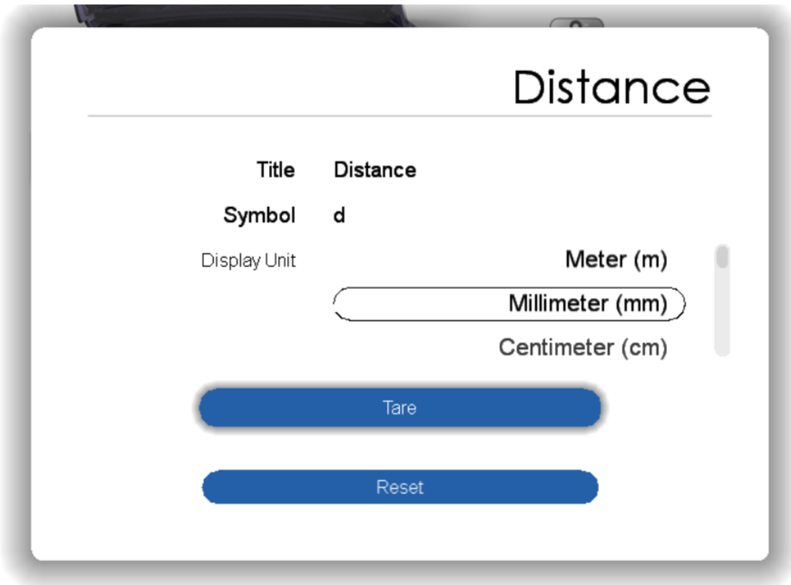


Figure 5: Tare the displacement readings in Quantities Panel > Displacement > Tare when the plunger is at its minimum position, i.e., farthest away from the PhysDisp.

4. Once distance has been configured in the App, go to Extensions Menu > Build from Scratch > Arithmetic > Multiply. This adds a Binary Multiplier to your workspace so you can calculate Volume using displacement readings from PhysDisp.

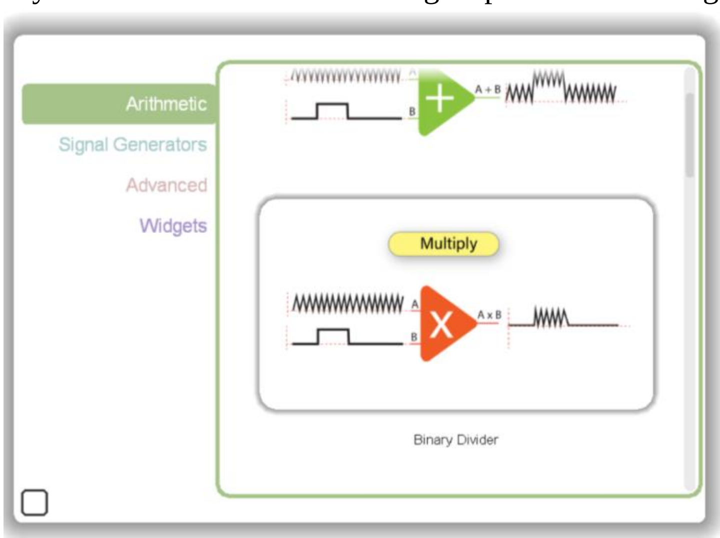


Figure 6: Extensions Menu > Build from Scratch > Arithmetic > Multiply will create a Binary Multiplier to compute volume using displacement readings from PhysDisp.

5. The binary multiplier can be renamed, e.g., we renamed it as `Volume` (see Figure 7). The `Distance` (readings from PhysDisp) is multiplied with the cross sectional area of the barrel of the syringe. The cross sectional area is:

$$\text{Quantity B (cross sectional area of barrel)} = -\frac{\pi}{4} \times I.D^2,$$

where I.D is the internal diameter of the barrel. The negative symbol is used because the volume of the syringe increases as the plunger moves upwards, i.e., as the distance between the object (plunger) and the sensor (PhysDisp) decreases, the volume increases

An upward moving plunger is equal to expanding air and increasing volume and will be demonstrated as an increase in the LivePlot as well.

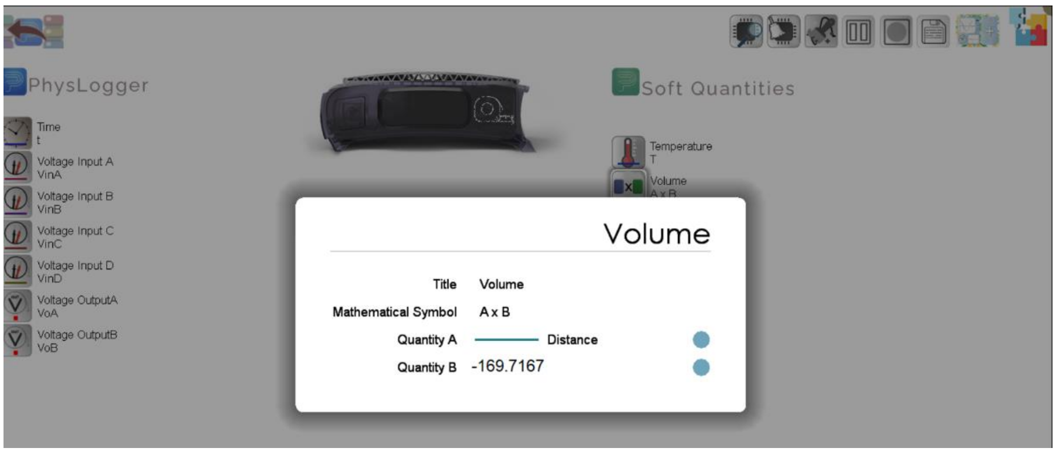


Figure 7: In the Binary Multiplier (renamed as Volume here) `Distance` from PhysDisp is multiplied with the cross-sectional area of the syringe plunger to calculate the volume of the syringe. -169.7167 was the internal cross sectional area of our syringe, it will vary for your syringe. Measure the internal diameter of your syringe with a vernier caliper!

6. This created soft quantity of Volume can then also be dragged and dropped on a LivePlot to be monitored and recorded.

5. Experimental Procedures

5.1. Boyle's Law:

We'll start from the simplest law of gas. Boyle's Law tells us that pressure *P* is directly proportional to volume *V* when temperature *T* is kept constant, i.e., $PV = constant$.

1. Connect the syringe through the nylon tube to PhysBar.
2. PhysBar is connected to one of the Digital Channels of the PhysLogger.
3. In PhysLogger Desktop, go to `Measure > Pressure`.
4. Observe how the pressure varies on the LivePlot of PhysLogger Desktop App as you increase and decrease the volume of the air inside the syringe by expanding and compressing the syringe.

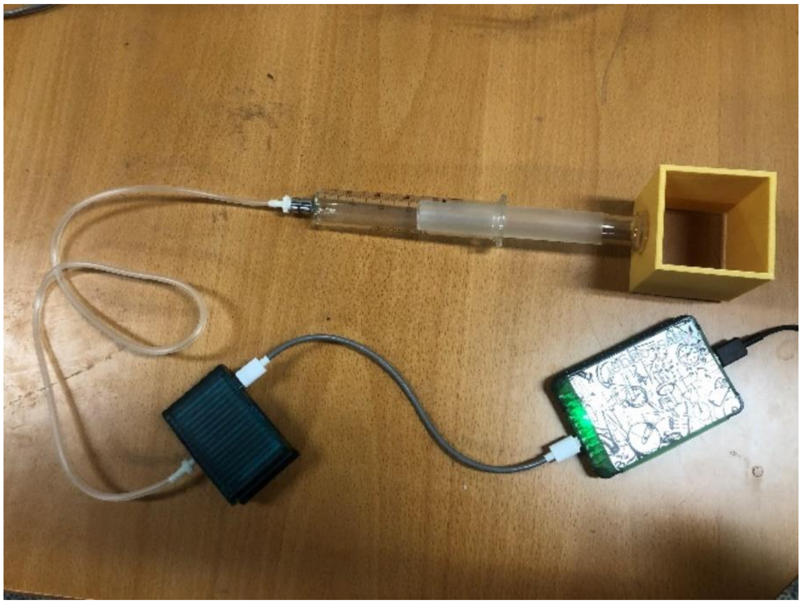


Figure 8: To investigate Boyle's law qualitatively, directly connect your syringe with PhysBar.

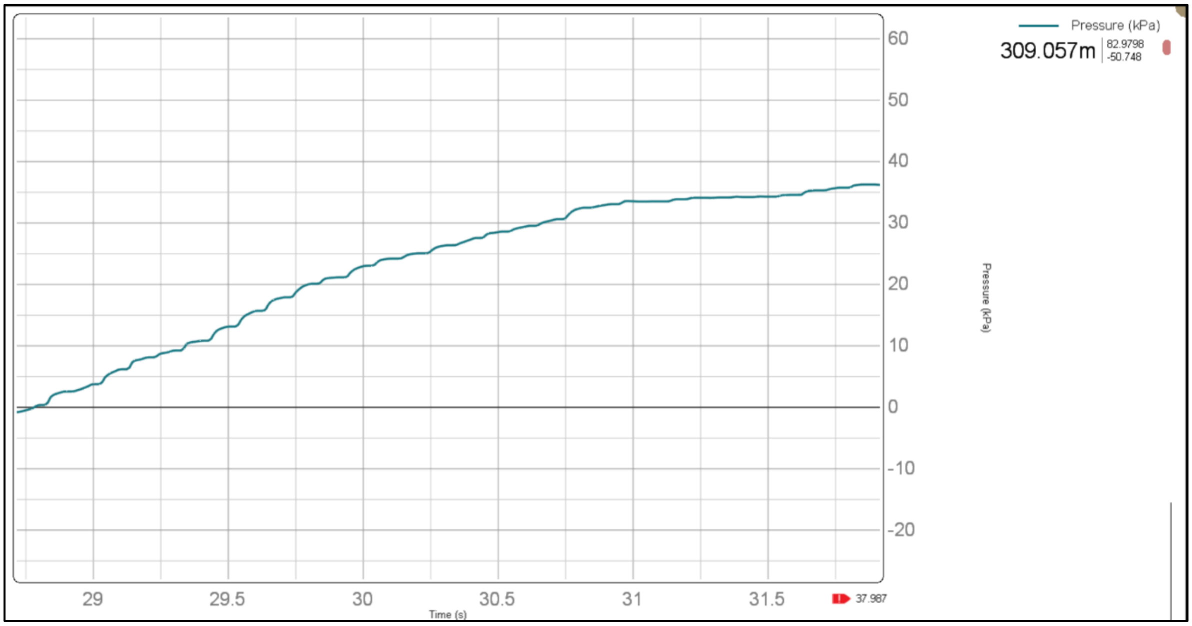


Figure 9: Pressure is plotted on the vertical axis against time. Pressure is observed to rise as the syringe is being compressed. For simplicity, here we observe the volume visually using the graduations on our syringe. (Try improving this graph by perhaps quasi-statically changing the volume so the temperature does remain as close as constant to possible.)

5.2. Charles's Law:

In this part of the experiment, we will not use PhysBar. Charles Law states that the volume V of a gas is directly proportional to temperature T when the pressure P remains constant, i.e., $V \propto T$.

1. Connect Thermocouple to PhysTherm and correctly position the PhysDisp vertically above the syringe. Both PhysInstruments are connected to PhysLogger.
2. A tubing connects the copper coil (placed inside a beaker with water) to the syringe.
3. Initially the coil, together with the thermocouple, are placed in a cold-water bath (i.e., at room temperature).
4. Simultaneously, heat another beaker containing water on the hot plate.
5. In PhysLogger Desktop App, LivePlot `Temperature` and `Volume`. You may also plot both these quantities against each other.
6. Once the beaker on the hot plate has been heated enough (approximately 90 ^{0}C), transfer the coil and thermocouple from the cold water beaker to this heated water beaker, i.e., from cold to hot reservoir.
7. You shall immediately see a surge in the volume of the glass syringe and the syringe plunger springing upwards.

Note: If the temperature difference was sufficient, but you did not observe the desired change in volume, check your glass syringe for ***stickiness***. Also, ensure that all tubing connections are tight and there is no air leakage.

Figure 10: Experimental setup to observe the Charles's Law.

As the beaker containing water is heated, the coil and thus the air inside the coil is also heated up. This air expands, and its molecules travel through the tubing to the glass syringe, exerting pressure on the syringe plunger, and resulting in a rise in the volume of the syringe.

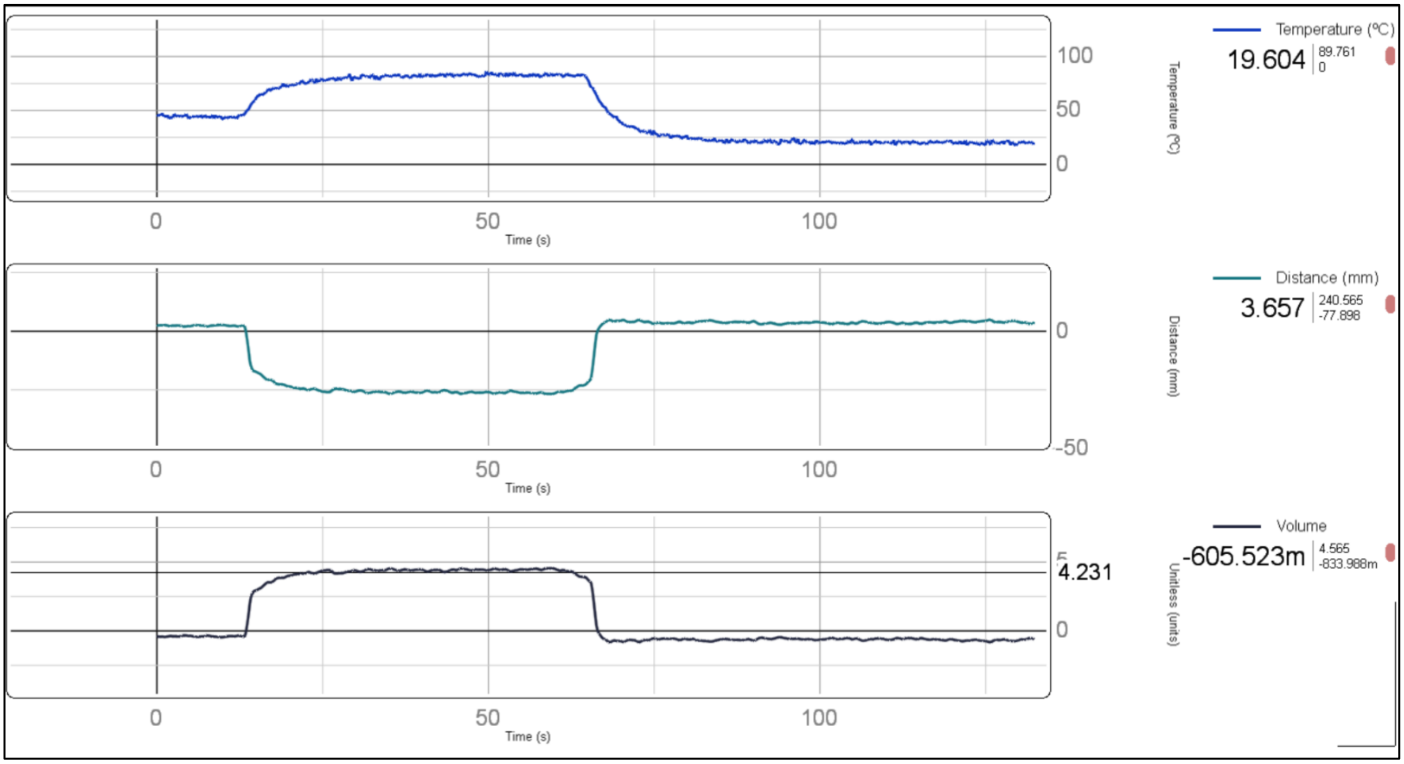


Figure 11: Pressure, Distance, and Volume (Volume is derived from Distance readings of PhysDisp) are plotted against time. The coil together with the thermocouple was placed in a hot water bath and then placed back in the cold water bath. The volume of the glass syringe is observed to vary similarly to how temperature of our gas varies (a visual representation of the Charles's Law). One may also plot Volume against Temperature.

5.3. Amonton's Law:

For the verification of this law, glass syringe and PhysDisp are not needed.

1. The copper coil is connected to PhysBar.
2. PhysBar is connected to a Digital Channel of Phsylogger in the usual way (refer to the section on Boyle's law).
3. The copper coil is immersed in about 150 mL of water inside a 250 mL beaker and placed on a hot plate.
4. A probe thermocouple is introduced inside the coil. The Thermocouple is attached to PhysTherm and the amplified output from this module reaches Analog Channel A of PhysLogger.

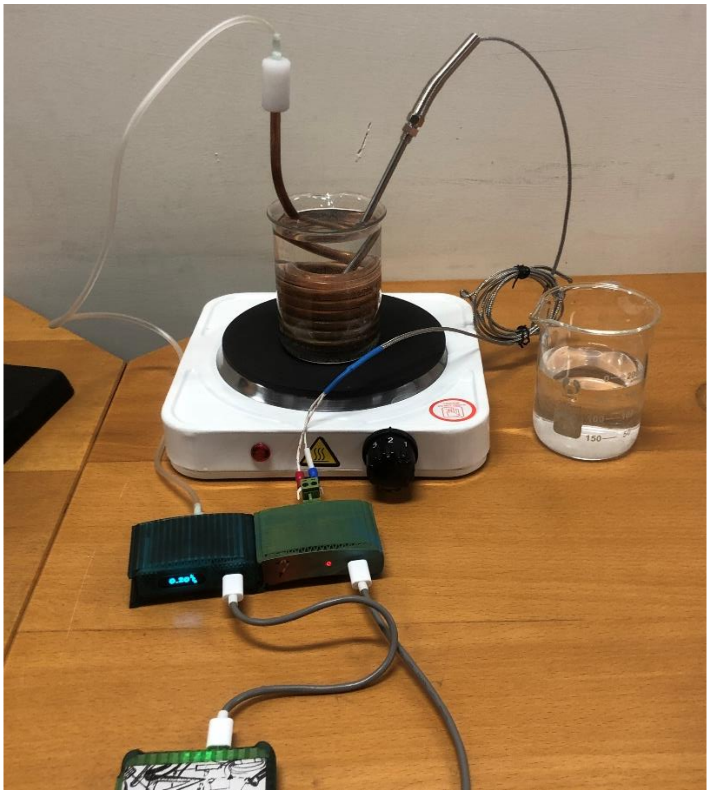
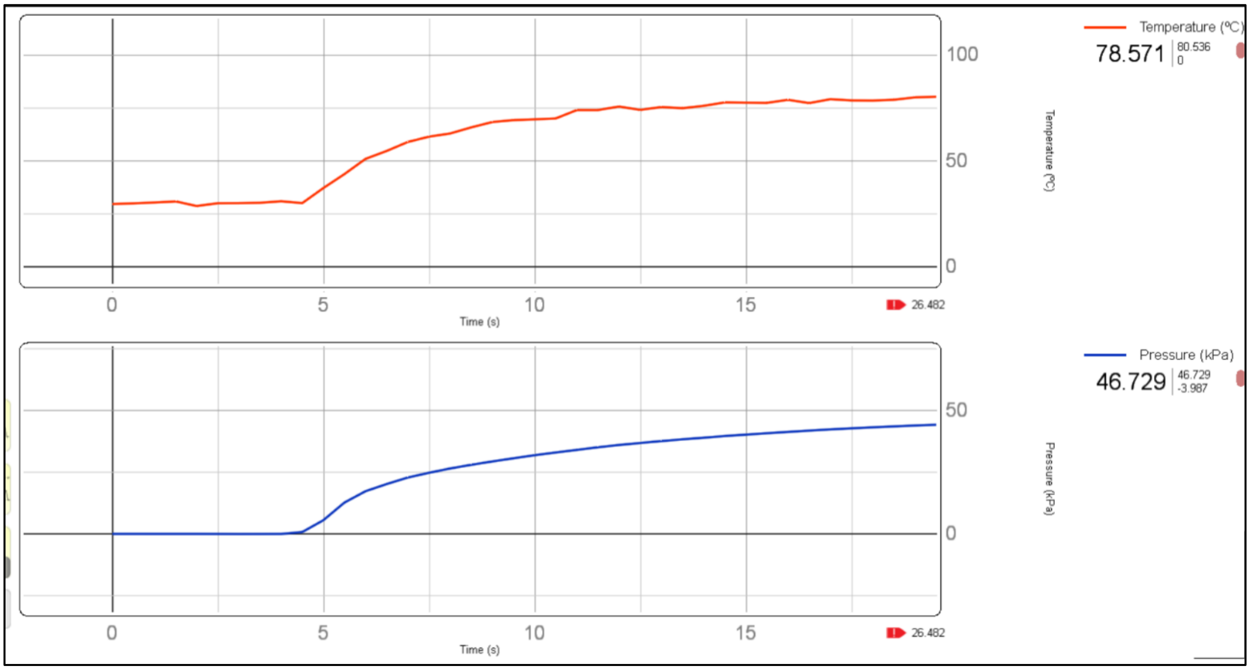
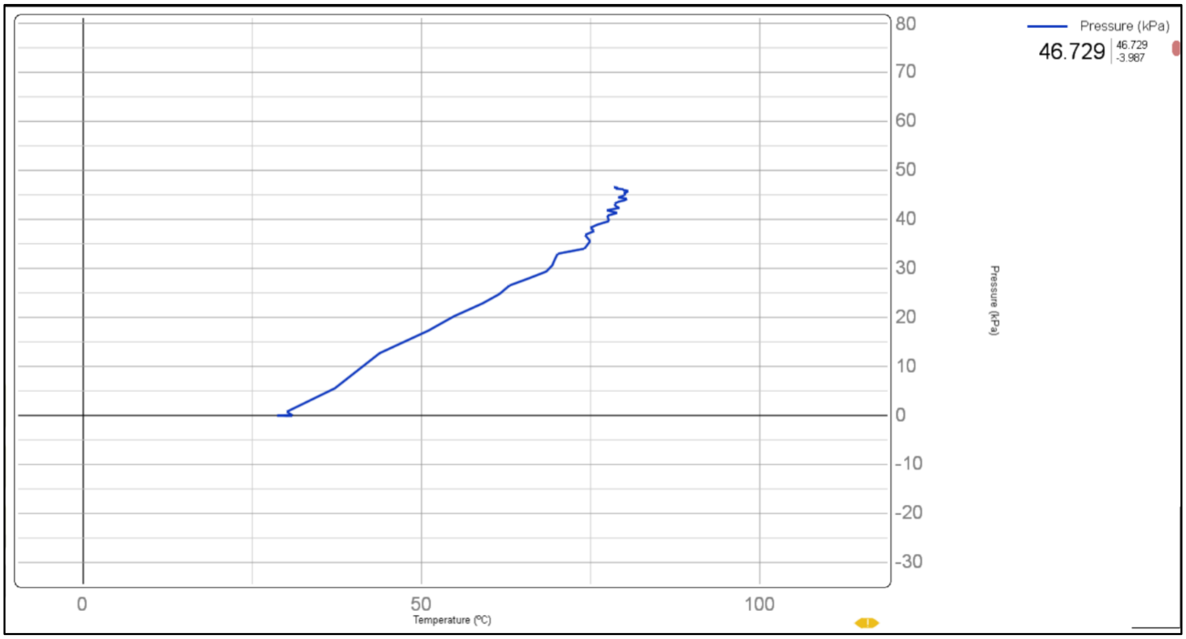


Figure 12: Experimental setup for verifying Amonton’s Law.



(a)



(b)

Figure 13: Some sample results of verifying Amonton's Law in PhysLogger Desktop App. These readings can of course also be exported for further analysis. Figure (a) shows a Cascaded LivePlots of Pressure and Temperature with time and (b) shows the LivePlot of Pressure against Temperature.

5.4. Investigating Heat Engine Cycles with PhysLogger

Using this experimental setup, PhysLogger and the relevant PhysIntruments, one can create and investigate a number of types of engine cycles. There is of course always the breadth of finding and resolving possible areas of inaccuracy to improve the system. Here, we present one engine cycle (shown in Figure 14) that was created using this setup. Students are encouraged to research on, create, and investigate additional cycles. The following reading may prove especially useful in this exercise [3].

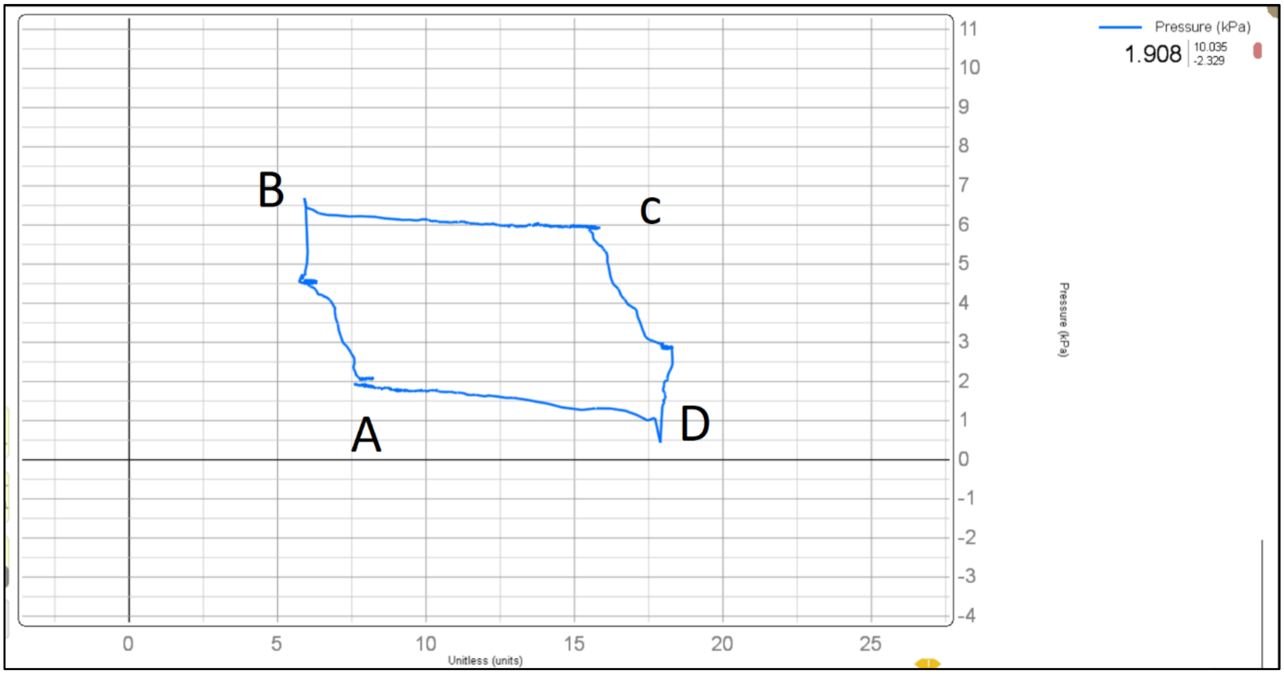


Figure 14: A LivePlot of Pressure (on vertical axis) against Volume (on horizontal axis), i.e., a PV diagram of a mass lifting heat engine cycle. This cycle is a reproduction of the cycle described in [3]. Students may compare this to an ideal cycle. A—B is equivalent to isothermal compression (placing a mass of 90g on piston); B—C: isobaric expansion (placed in hot reservoir); C—D: isothermal expansion (mass lifted); and D—A: isobaric compression (coil is placed back in cold reservoir)

1. Make all connections, as shown in Figure 1.
2. Initially, your plunger may be at 5 cc.
3. Configure all quantities in PhysLogger Desktop, these include Pressure, Volume, and Temperature (as described in Section 4).
4. At point A, the copper coil and thermocouple are placed in a cold water bath (i.e., beaker containing water at room temperature). No mass is placed on the mass holder.
5. From A to B, masses are slowly placed on the mass holder. (In our case this was 90 g of mass). The coil is still in the cold reservoir. Pressure is observed to rise as plunger moves downward due to increased load.
6. At point C, the coil and thermocouple are transferred to a hot reservoir. This is the beaker containing water that had been placed on hot water plate and would have been heated till up to ~90^{o}C. (The masses are still placed on the holder).
7. From point C to D, slowly remove the masses.
8. The coil is transferred back to the cold reservoir from point D to A.

References

1. PhysLab. *PhysLogger* Available from: https://physlab.org/facility/physlogger/
2. Qosain Scientific. *PhysLogger*. 2022; Available from: www.physlogger.com.
3. Jackson, D.P. and P.W. Laws, *Syringe thermodynamics: The many uses of a glass syringe*. American journal of physics, 2006. **74**(2): p. 94-101.