The University of Hong Kong
Department of Physics
Experimental Physics Laboratory


PHYS2260 Heat and Waves
2260-1 LABORATORY MANUAL
Experiment 1: Adiabatic Gas Law


## Part A. Ideal Gas Law

**Equipment Required:**
Adiabatic Gas Law Apparatus

**Purpose:**
To show that $\frac{PV}{T} = nR$ for an ideal gas and determine the value of $R$.

**Theory:**
The ideal gas law is the equation of state of an ideal gas. The well-known relationship between pressure, volume and temperature of an ideal gas is:

$$PV = nRT \tag{1}$$

where
$P$ is the absolute pressure of the gas measured in pascals (Pa),
$V$ is the volume of the gas measured in cubic metres ($m^3$),
$n$ is the number of moles in the sample (mol),
$T$ is the absolute temperature of the gas measured in Kelvin (K), and
$R$ is the ideal gas constant which has the value $8.314$ (J K⁻¹ mol⁻¹).

For a closed system with $n$ fixed, placing all variables on the left-hand side of the equation yields the constant value,

$$\frac{PV}{T} = nR \tag{2}$$

The number of moles, $n$, is related to the density of the gas ($\rho$), the molecular mass of the gas molecules ($M$), and the volume ($V$), via the relation,

$$n = \frac{\rho V}{M} \tag{3}$$

**Setup:**
**A. Connections:**
**1.** The Adiabatic Gas Law Apparatus (Figure 1) should have already been connected to *Science Workshop* 500 interface: the Pressure, Volume and Temperature din connectors are inserted into analog channels A, B and C of the interface, respectively.
**2.** Open *Capstone* on the computer. (Figure 2) Indicate that a *voltage* sensor is connected to each channel in the *Hardware Setup*. (Figure 3) Adjust the common *Sample Rate* to 1,000 Hz.
**3.** In the *Calculator* tool, click *New* and define the Pressure according to the linear calibration expression

on the label on the side of the Adiabatic Gas Law Apparatus. Provide the unit also. (Figure 3)
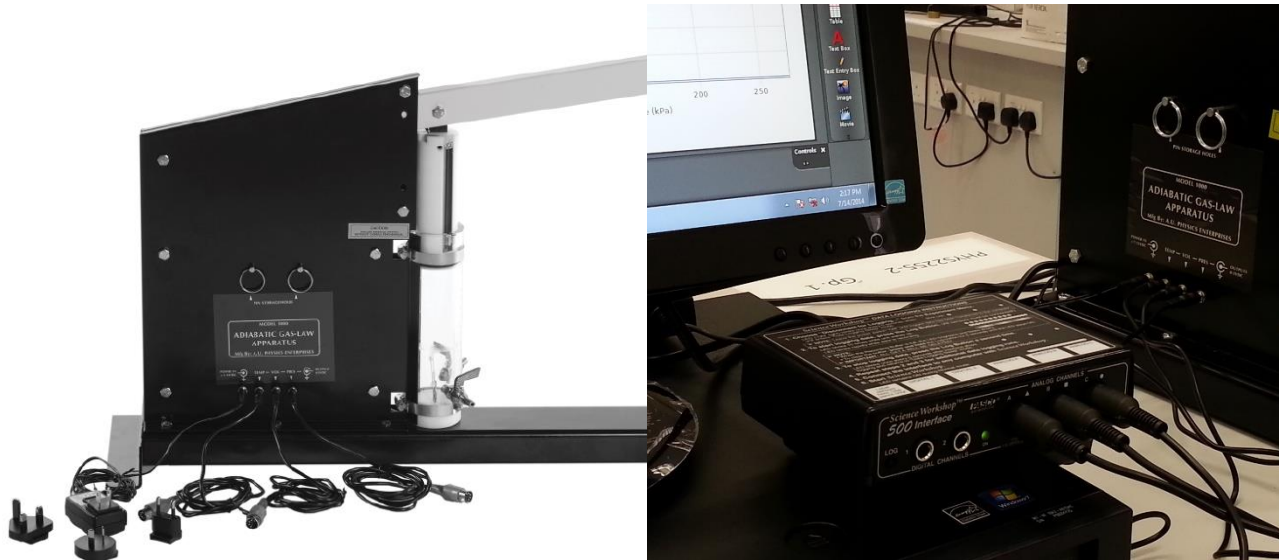**4.** Do the same for Volume and Temperature.



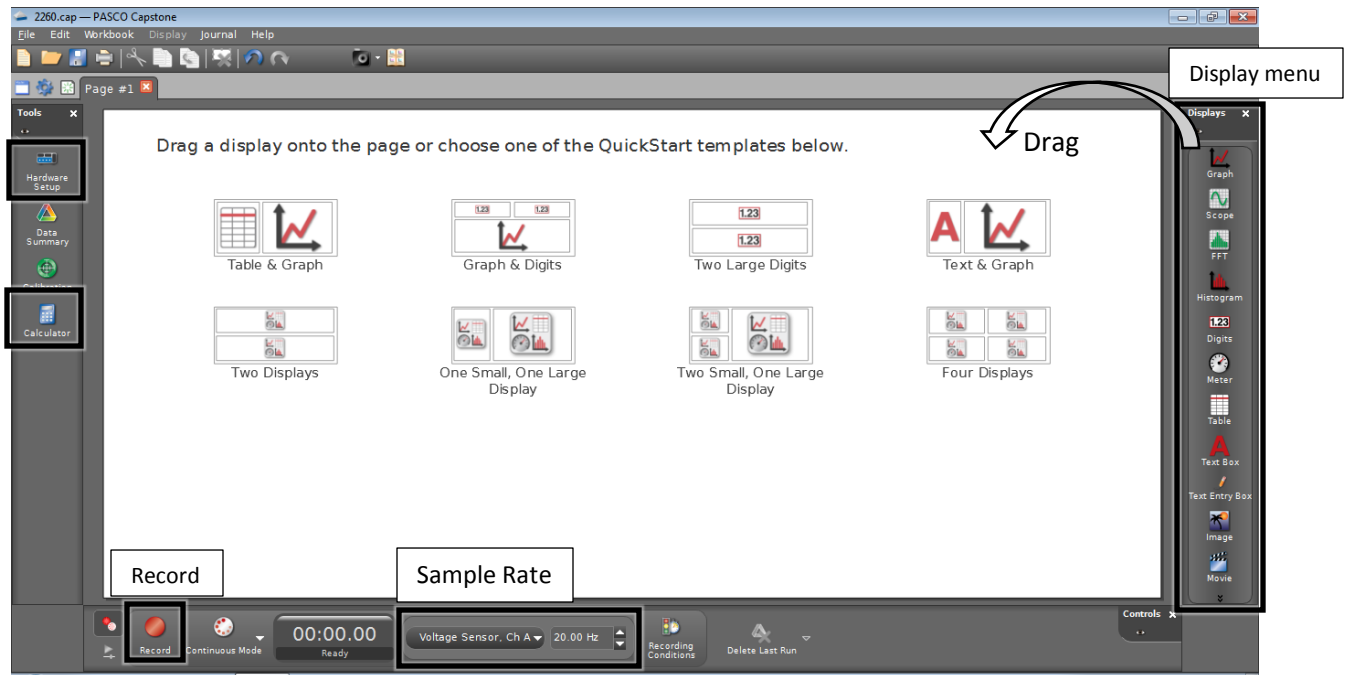Figure 1 – Adiabatic Gas Law Apparatus
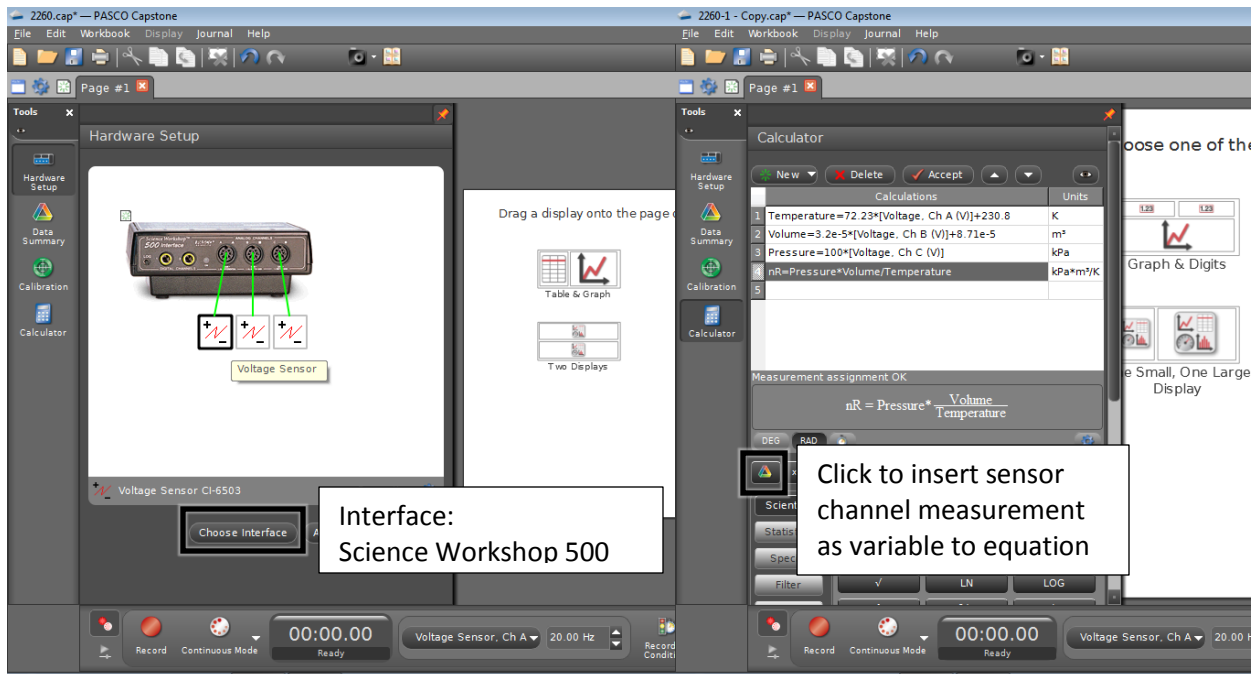


Figure 2 – Software overview

Figure 3 – Hardware setup and Calculator

**B. Graphical Display:**

**1.** Drag-and-drop the *Graph* icon from the *Displays* menu onto the page. On the y-axis, select measurement to be Pressure that is defined under the Equations/Constants label. Select Time(s) for the x-axis.

**2.** Repeat step 2 for Volume and Temperature. In this way, graphs of Pressure, Volume and Temperature will all be displayed with a common time axis. (Figure 4)
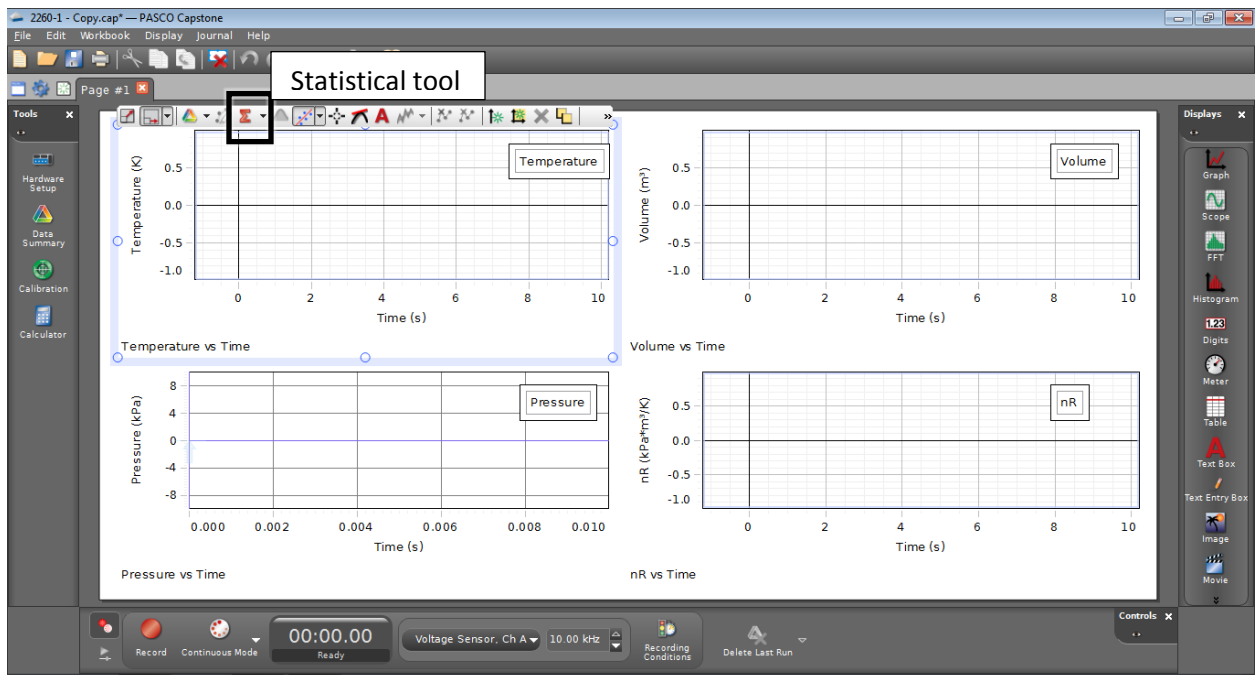

Figure 4 – Example of Graphical display

**Procedure:**
**1.** With a stopcock valve open, set the piston to the approximate middle of its range at the 10 cm mark and close both stopcocks.
**2.** Record the height of the piston at atmospheric pressure.
**3.** Raise the piston to its highest position, click on *Record* and, over a span of approximately five seconds, slowly and steadily move the piston to its lowest position, then click *Stop*. Notice that the graphs plotted show the Pressure increasing as the Volume decreases.

**Analysis:**
**A. Conversions from voltages to $P$, $V$ and $T$**
**1.** Use the *Calculator* to define $nR = P \cdot V/T$ and choose Properties to ensure that the Numeric display shows at least three significant figures. Plot a graph of $nR$ by selecting the appropriate title on the vertical axis.
**2.** Use the $\Sigma$ icon on the *Graph* menu to display the mean value of $nR$ as well as the standard deviation.
**3.** Record the mean value and also the standard deviation of $nR$. Estimate the random error associated with the experiment.

**B. Number of moles, $n$**
**1.** Calculate the volume of air (in cm$^3$) at the initial 10 cm height when the stopcock was open to the atmosphere using $V_0 = \pi r^2 h_0$ where $r$ is half the diameter displayed on the label of the Adiabatic Gas Law Apparatus.
**2.** Calculate the number of moles of gas from equation (3), with the density of air at standard temperature and pressure (STP) of $\rho = 0.00129$ g/cm$^3$, the volume $V_0$, and the molecular weight of air $M_{air} = (0.8 * 28 + 0.2 * 32)$ g/mol (assuming 80% nitrogen and 20% oxygen).
**3.** Compute your measured value of $R$ using the relationship $R_{mean} = (nR_{mean})/n$
**4.** Compare your measurement with the generally accepted value of $R$.

## Part B. Adiabatic Gas Law

**Equipment Required:**
Adiabatic Gas Law Apparatus, Helium (or Argon) gas, Carbon dioxide gas

**Purpose:**
To observe the adiabatic gas law $PV^\gamma = constant$ and measure the ratio of specific heats, $\gamma$, for various gases.

**Theory:**
When a process occurs quickly enough that no heat is exchanged with the environment ($Q = 0$), the process is considered "adiabatic". For such process, the relation between pressure $P$ and volume $V$ is given by

$$PV^\gamma = constant \qquad (4)$$

Here $\gamma$ is the ratio of specific heats at constant pressure and constant volume, i.e.,

$$\gamma = \frac{c_P}{c_V} \qquad (5)$$

A measurement of $\gamma$ reveals important physical information about the structure of the gas molecules. The equipartition theorem tells us that the molar specific heat at constant volume $c_V$ is related to the number of degrees of freedom, $f$, available to each molecule through the relation

$$c_V = \frac{f}{2}R \tag{6}$$

where $f = 3$ for a monatomic gas with three translational directions of motion, and $f = 5$ for a diatomic gas with three translational plus two rotational contributions to the internal energy.

The specific heat at constant pressure, $c_P$, is related to the specific heat at constant volume by

$$c_P = c_V + R \tag{7}$$

Thus, a monatomic gas like Helium (He) or Argon (Ar) with $f = 3$ has the ratio $\gamma = \frac{(3/2+1)R}{(3/2)R} = 5/3$.

A diatomic gas like the Nitrogen ($N_2$) and Oxygen ($O_2$) has $\gamma = \frac{(5/2+1)R}{(5/2)R} = 7/5$.

Carbon dioxide ($CO_2$) has more complex degrees of freedom such that $\gamma = 1.30$.

Experimentally, you will determine $\gamma$ by observing the relation between pressure and volume. Since equation (4), the adiabatic gas law, can be rewritten as

$$\ln(P) = -\gamma \ln(V) + \ln(constant) \tag{8}$$

One sees that a plot of $\ln(P)$ vs. $\ln(V)$ should be a straight line with a slope of $-\gamma$.

**Setup:**
Same as the one in **Part A. Ideal Gas Law**.

**Procedure:**
**1.** With a stopcock valve open, set the piston to the approximate middle of its range at the 10 cm mark and close both stopcocks.
**2.** Raise the piston to its highest position, click on *Record* and, this time quickly move the piston to its lowest position, then click *Stop*. The gas should be compressed as rapidly as possible to make the experiment approximately adiabatic.

**Analysis:**
**1.** Use the *Calculator* to compute the $\ln(P)$ and $\ln(V)$ and make a graph of $\ln(P)$ on the y-axis vs. $\ln(V)$ on the x-axis. Perform a linear fit and record the slope. For air, compare this with the value 1.40.
**2.** Repeat the experiment using argon (or helium) and $CO_2$ comparing with the respective ratios for these gases. Read **Appendix A and B** for inserting gas from gas cylinder into the apparatus.

## Part C. Work Done by an Adiabatic Process

**Equipment Required:**
Adiabatic Gas Law Apparatus

**Purpose:**
To observe that the work performed on a gas is given by $W = \int P dV$, i.e., the area under a $P$ vs $V$ curve.

**Theory:**
When a gas is compressed under constant pressure, the work performed on the system is simply the product of force times displacement:

$$W = -F\Delta y = -PA\Delta y = -P\Delta V \tag{9}$$

If the pressure changes as the compression occurs, the work done on the gas becomes the integral:

$$W = - \int_{V_i}^{V_f} P dV \tag{10}$$

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corresponding to the negative of the area under a Pressure vs Volume curve.

If the compression occurs adiabatically, there is no heat exchange with the environment and by the First Law of Thermodynamics the change in internal energy will equal the work performed on the gas,

$$\Delta U = Q + W = W \qquad (11)$$

Thus, when the gas is compressed adiabatically, we can measure the area under the $P$ vs $V$ curve and compare with the change in internal energy given by,

$$\Delta U = \frac{f}{2}nR\Delta T \qquad (12)$$

for an ideal gas with $f$ degrees of freedom.

For the diatomic molecules of air ($f = 5$) this becomes,

$$\text{Area under P vs V curve} = \frac{5}{2}nR\Delta T \qquad (13)$$

One can also analytically calculate the area under the $P$ vs $V$ curve by noting

$$W = -\int_{V_i}^{V_f} P dV = -k \int_{V_i}^{V_f} \frac{dV}{V^\gamma} = -k\left[\frac{V^{1-\gamma}}{1-\gamma}\right]_{V_i}^{V_f} = \frac{P_i V_i^\gamma}{\gamma - 1}\left(V_f^{1-\gamma} - V_i^{1-\gamma}\right) = \frac{P_i V_i}{\gamma - 1}\left(r^{\gamma-1} - 1\right) \qquad (14)$$

where $r = V_i/V_f$ is the compression ratio.

**Setup:**
Same as the one in **Part B. Adiabatic Gas Law**.

**Procedure:**
Follow the procedure for **Part B. Adiabatic Gas Law**.

**Analysis:**
**1.** Construct a plot of Pressure vs Volume and expand the view appropriately. Using the "Area under active data" button, record the area under the $P$ vs $V$ curve.
(**Be careful** to highlight data that avoids both ends of the $P$ vs $V$ curve! The numerical integration breaks down when the ends are included.)
**2.** Plot Temperature vs time and use the Statistics (Σ) to record the minimum and maximum temperature and compute the change in the temperature.
**3.** Calculate the volume of air (in cm³) at the initial 10 cm height when the stopcock was open to the atmosphere using $V_0 = \pi r^2 h_0$ where $r$ is half the diameter displayed on the label of the Adiabatic Gas Law Apparatus.
**4.** Calculate the number of moles of gas from equation (3), with the density of air at STP of $\rho = 0.00129$ g/cm³, the volume $V_0$, and the molecular weight of air $M_{air} = (0.8 * 28 + 0.2 * 32)$ g/mol (assuming 80% nitrogen and 20% oxygen).
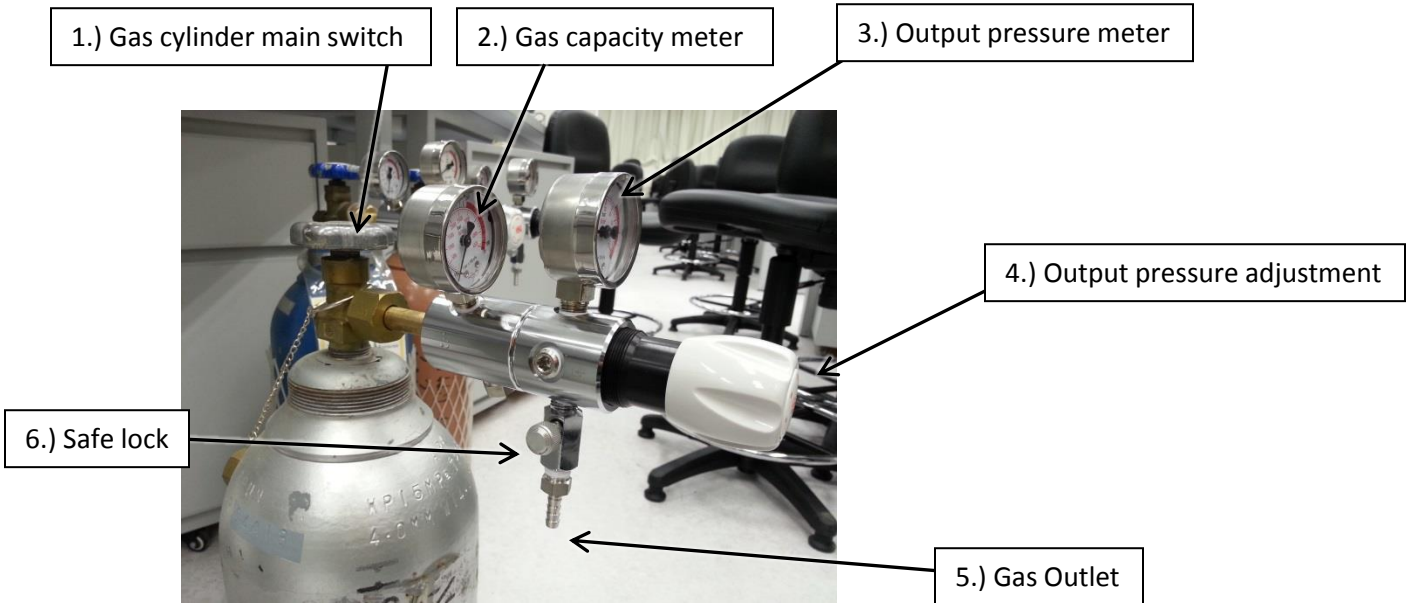**5.** Compute the change in internal energy of the air using equation (13).
**6.** Compare the change in internal energy with the area under the $P$ vs $V$ curve.
**7.** Compare the area under the curve with the prediction of equation (14).

**Appendix A. Gas Cylinder Operation**

**Gas Cylinder side view**

1.) Gas cylinder main switch    2.) Gas capacity meter    3.) Output pressure meter

4.) Output pressure adjustment

6.) Safe lock

5.) Gas Outlet

1.) Gas cylinder main switch: turn clockwise to lock and anti-clockwise to open.
2.) Gas capacity meter: to show the existing gas capacity remained.
3.) Output pressure meter: please adjust the output pressure adjustment (4) to knob within 2 bar.
4.) Output pressure adjustment: clockwise to open and anti-clockwise to close.
5.) Gas outlet: for piping connection or your device.
6.) Safe lock: anti- clock wise to provide gas and clockwise to stop the gas output

**Gas cylinder regulator and outlet front view**

Output pressure meter

Gas capacity meter

Safe lock

Output pressure adjustment

Gas outlet
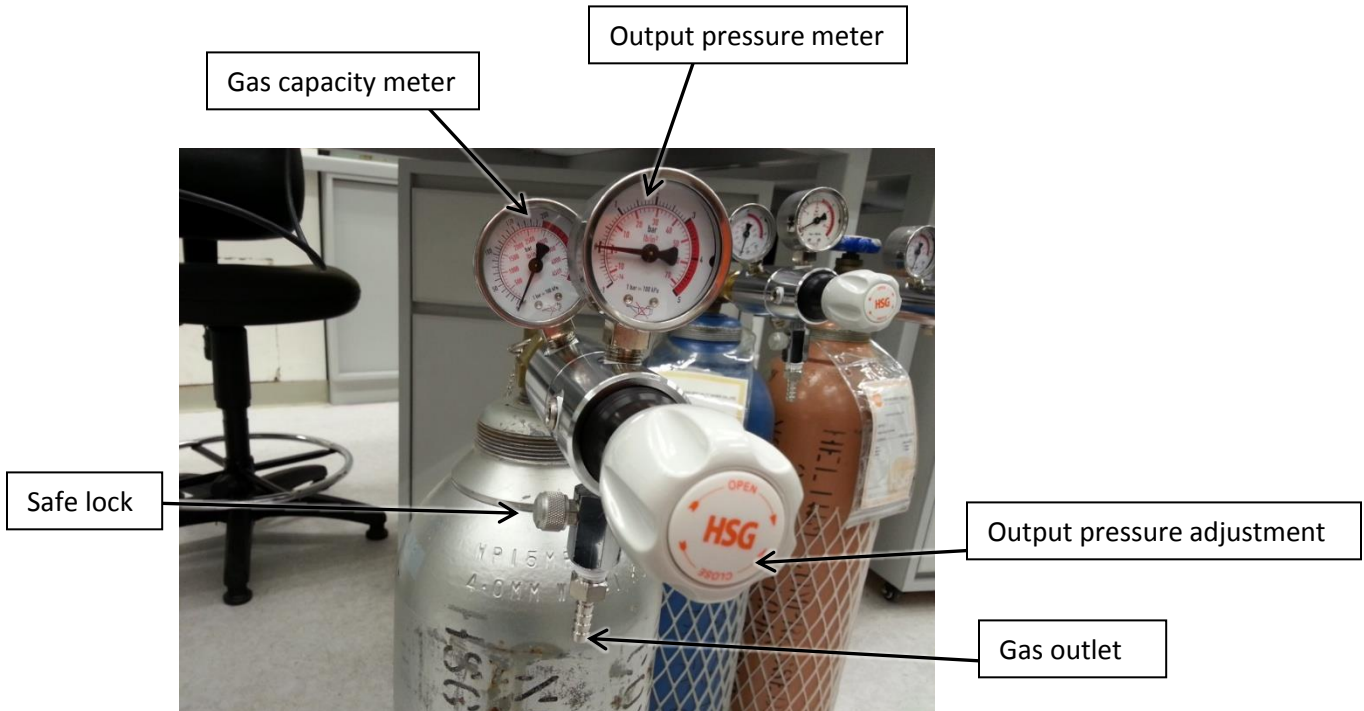
**Appendix B. Connection between Gas Cylinder and Adiabatic Gas Law Apparatus**

| | |
|---|---|
|  | A brass gas cock with a short hose (like pig tail) is fixed on the Adiabatic Gas Law Apparatus. When the hose is free from connection, normal air is applied to the experiment. |
|  | Close state of the brass gas cock. The gas inlet and outlet are blocked. The handle is in 90 degrees with the hose. |
|  | Open state of the brass gas cock. The gas inlet and outlet are allowed. The handle is aligned with the hose. |

| | |
|---|---|
|  | A piece of easy connection adaptor in top view. An easy connection adaptor is usually used as hose connection in simple management. Both ends of the blue ring are the lock and unlock switches for mount and dismount of the hose. Students can apply this accessory to connect different gases to the Adiabatic Gas Law Apparatus. |
|  | Side view of the easy connection adaptor. |
|  | An easy connection adaptor connected to the hose with the tap on the apparatus. |
|  | Students just need to insert the hose end into one end of the easy connection adaptor. The blue ring (as pointed by pencil) will lock and seal automatically, when well connected. |

|  | About the easy connection adaptor:<br>The blue ring down the adaptor body shows that the lock to the hose has completed. To dismount the hose, push the blue ring down into the body and then pull out the hose. |
| --- | --- |
|  | A hose with easy connection adaptors on both sides. This hose is used for connection between the gas cylinder and the Adiabatic Gas Law Apparatus. (For example: carbon dioxide, helium and argon gas) |

**Steps and operation hints of filling special gas (Carbon dioxide, Helium and Argon) to the apparatus.**

Please follow the below steps for special gas to fill up the cylinder of apparatus:-

1.) Student need to check the gas type and location as their needs. (Gas cylinder is labeled.)
2.) Turn safe lock on gas regulator in clock-wise direction for closure.
3.) Turn output pressure adjustment on gas regulator in anti-clockwise direction for closure. (Output pressure meter shows zero)
4.) Turn on (in anti-clockwise direction) Gas cylinder main switch as open for gas to be ready to supply.
5.) Adjust the output pressure adjustment by turning in clockwise direction and observe the pressure meter which reveals that the output reading is maintained within 1.5 – 2.0 bar.
6.) Turn both stopcock (A & B) open on the cylinder of apparatus (stopcock A & B addressed in the base of the cylinder; photos in Appendix B for reference), student can identify stopcock A and B by themselves. (Turn both stopcock A and B open, making the condition ready for gas to fill up.)
7.) Connect the hose with easy connection adaptor to the stopcock A. Then leave stopcock B for free and turn open.
8.) Student need to turn on the safe lock on gas regulator for around 20s, this is a simple management to allow gas flow via stopcock A in and out from stopcock B. This approach is needed to allow the special gas to flow in with high concentration and pressure to force the existing atmosphere air/gas molecules move out from the stopcock B. (Student can use your hand or skin to feel the air flow from this stopcock B outlet.)
9.) When student is ready to fill the gas for the cylinder, turn off the stopcock B. (Please pay attention that the special gas will flow into the cylinder and the handle may rise suddenly to cause injury!) So, a fine tune/gentle adjustment to the safe lock to control the gas flow into cylinder is the appropriate management to avoid some accident and damage to the apparatus.

**Reminder:** Strong adjustment on safe lock may cause the gas overflow/high flow rate with strong momentum! It may lead to instant upward movement of the apparatus and the cylinder with handle. As it is very dangerous for the handle and cylinder to rise under this unexpected condition, student and your group-mate may get injured!

**Recommendation:** When a student is applying the special gas to fill up the cylinder of the apparatus, other group-mates please stay away from the apparatus and pay attention to its handle and its sudden rise! About the operation, student may use the safe lock to fine tune the gas flow with gentle adjustment. This can help your group-mate to observe the slowed down movement of the handle to avoid injury and accident.

10.) After the gas fills up the cylinder of apparatus, student needs to take the measurement of the capacity reading over the cylinder (its height and diameter for volume calculation) and turn off the stopcock A as completion.
11.) Turn off/close the safe lock (in clockwise direction) on the gas cylinder regulator.
12.) Turn off / close the output pressure adjustment (in anti-clockwise direction) on the gas cylinder regulator. Please keep the output pressure meter at Zero reading!
13.) Turn off / close the gas cylinder main switch (in clockwise direction).