# Studying Charles' Law

## Introduction

Charles' Law states that the volume of a fixed amount of ideal gas is proportional to its thermodynamic temperature at constant pressure:

$$V \propto T \quad \text{or } V = kT$$

where *V* is the volume, *T* is the temperature in *K*, and *k* is a constant.

This also means that the ratio of volume and temperature is the same at any temperature:

$$k = \frac{V_1}{T_1} = \frac{V_2}{T_2} = \frac{V_3}{T_3} = \ldots$$

In this experiment you will measure the volume of an air sample enclosed in a syringe at constant pressure at different temperatures. If the plunger is at rest, the pressure inside is the same as outside (see Figure 1.), which in this case is the atmospheric pressure (1.0 atm). If the temperature of the syringe changes, the plunger moves accordingly until the pressure inside the syringe and outside are the same.

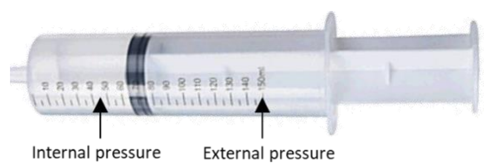



Figure 1. Syringe for Charles' Law

As an example, consider a 10-mL syringe placed into baths with different temperatures. The collected readings and the converted temperature values to K and volume to L are shown in Figure 2. The respective *V* vs. *T* graph is shown in Figure 3.

| Measurements | | Converted measurements | |
|---|---|---|---|
| T (°C) | V (mL) | T (K) | V (L) |
| 67.0 | 8.0 | 340.0 | 8.0E-03 |
| 47.0 | 7.5 | 320.0 | 7.5E-03 |
| 35.0 | 7.3 | 308.0 | 7.3E-03 |
| 21.0* | 6.9* | 294.0 | 6.9E-03 |
| 5.5 | 6.7 | 278.5 | 6.7E-03 |
| 0.0 | 6.5 | 273.0 | 6.5E-03 |
| -6.0 | 6.4 | 267.0 | 6.4E-03 |

*Room temperature measurement

Figure 2. Collected and calculated sample data

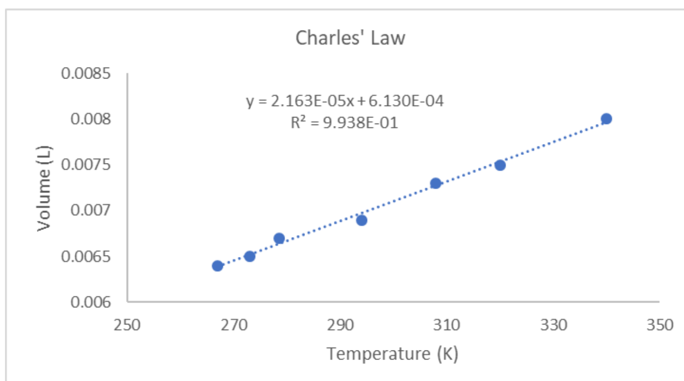



Figure 3. *V* vs. *T* graph of sample data

The amount of air in the syringe (using the room temperature readings of *T*=21 °C and *V*=6.9 mL)[1]:

$$n = \frac{pV}{RT} = \frac{\left(1.0\,\cancel{\text{atm}}\right)\left(6.9\times10^{-3}\,\cancel{\text{L}}\right)}{\left(8.206\times10^{-2}\,\frac{\cancel{\text{L}}\,\cancel{\text{atm}}}{\text{mol}\,\cancel{\text{K}}}\right)\left(294\,\cancel{\text{K}}\right)} = 2.86\times10^{-4}\,\text{mol}$$

[1] The volume reading has two significant figures, however an extra significant figure is carried through the calculations and the final result is rounded properly.

Using the Ideal Gas Law, the slope of the *V* vs. *T* graph *should be* with constant *p* and *n*:

$$pV = nRT$$

$$\underset{\substack{\text{dependent}\\\text{variable}}}{V} = \underset{\text{slope}}{\frac{nR}{p}} \underset{\substack{\text{independent}\\\text{variable}}}{T}$$

From the slope *R* can be estimated:

$$(\text{slope}) = \frac{nR}{P} \rightarrow R = \frac{(\text{slope})P}{n} = \frac{\left(2.16\times10^{-5}\,\frac{\text{L}}{\text{K}}\right)(1.0\text{atm})}{\left(2.86\times10^{-4}\text{mol}\right)} = 7.55\times10^{-2}\,\frac{\text{L atm}}{\text{mol K}} \rightarrow 7.6\times10^{-2}\,\frac{\text{L atm}}{\text{mol K}}$$

The % error of the measurement is assessed by comparing the theoretical and experimental estimate of *R*:

$$\%\ \text{error} = \frac{\left|8.206\times10^{-2} - 7.6\times10^{-2}\right|}{8.206\times10^{-2}}\times100\% = 8.0\%$$

(units are omitted as they cancel out)

In this experiment you will place the syringe with the air sample into five water baths with different temperature values and measure the volume of the sample.

**Procedure**

1. Place a 1000-mL beaker ¾ full with tap water on a hot plate and start heating it. Check the temperature periodically and do not allow it to go higher than 80 °C. Replenish the water during the experiment as needed.
   <u>**Note:**</u> When handling the beaker with hot water, use insulated gloves, apply a firm and secure grip on the beaker, and hold it way from yourself and others.
2. Remove the cap from a 20-mL syringe. Remove the plunger and apply a very thin layer of silicone grease on the edge of the plunger. Replace the plunger and move it in and out a few times to make sure that it moves easily.
3. Set the plunger to 15.0 mL, replace the cap and make sure it is airtight. Push in the plunger gently, and allow it to bounce back freely.
4. Record the volume and the room temperature in the data table below.
5. Assemble the setup as shown in Figure 4., except the bath. Mount the syringe right below the tabs of the syringe. Raise the thermometer and the syringe with the clamp high enough that the 400-mL beaker would fit underneath.
6. There will be five baths used with different temperatures (in addition to the room temperature measurement), setup in a 400-mL beaker, prepared one at a time:
   - **Beaker 1**: Fill the beaker with ice, sprinkle table salt on the ice, and mix it with a spatula. <u>**Note:**</u> If the ice hardens due to the temperature drop, break it up with the spatula and not with the thermometer.
   - **Beaker 2**: Fill the beaker 1/3rd with ice, add some water and mix. Check the temperature which should be close to 0 °C. Some ice should remain through the experiment. Add more ice if needed.
   - **Beaker 3**: Fill the beaker ¾ with tap water and add enough ice so that the temperature is between 10-12 °C.
   - **Beaker 4**: Fill the beaker about ½ with tap water and add enough hot water to set the temperature between 35-40 °C. If the beaker is getting too full, dispose some of the water.

- **Beaker 5**: Fill the beaker about ¼ with tap water and add enough hot water to set the temperature between 55-60 °C. If the beaker is getting too full, dispose some of the water.

7. Prepare the bath for Beaker 1. as described above.
8. Place the bath under the syringe and the thermometer, and lower both into the bath.
   **Note:** For the ice bath make sure that the ice is loose, and it can readily accommodate the syringe and the thermometer. If necessary, make room for them with the spatula.
9. Keep the syringe in the bath for 5 min. Gently mix/swirl the bath, periodically.
10. While waiting, in a separate 400-mL beaker setup the next bath.
11. When the 5 min is up for the first bath:
    - record its temperature
    - lift the thermometer and the syringe out of the bath
    - quickly remove the syringe from the clamp
    - gently push the plunger in and allow it to freely bounce back
    - read the volume to the nearest 0.1 mL.

    **Note:** try to minimize the time between removing the syringe and taking the volume reading.
12. Repeat steps 8-11 with the remaining baths.
13. When done, dispose the contents of the beakers into the sink, and clean the glassware with tap water and a final rinse with distilled water.

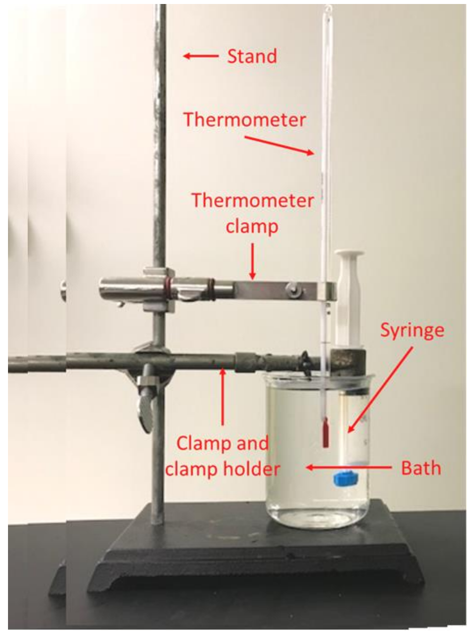


Figure 4. Bath for different temperatures

**Data Table/Calculations**

1. Complete the data table.

| Bath | T (°C) | T (K) | V (mL) | V (L) |
|---|---|---|---|---|
| Beaker 1: | | | | |
| Beaker 2: | | | | |
| Beaker 3: | | | | |
| Room temp: | | | | |
| Beaker 4: | | | | |
| Beaker 5: | | | | |

**Note:** For the calculations and graphing use a spreadsheet application (e.g. Excel, see Appendix).

2. Create a plot of $V$ vs. $T$ (use the converted units). Record the slope and intercept (with units):

Slope:____________ Intercept:__________

Make sure:

- The graph is properly scaled to maximize the real estate of the graph with your points.
- The axes are properly labelled with the respective quantities and units.
- Trendline is added with the equation and $R^2$ value.
- The numbers on the axes and in the equation (trendline label) are properly formatted with the right number of significant figures.

3. Using the Ideal Gas Law ( $pV = nRT$ ), calculate the number of moles of air in the syringe using the room temperature data.

$n =$ ______ mol

4. Using the Ideal Gas Law, and the number of moles of air in the syringe, calculate the expected volume at each temperature.

| Temperature (K) | Volume (L) | |
|---|---|---|
| | Experimental (from the table above) | Expected |
| | | |
| | | |
| | | |
| | | |
| | | |

5. Add the expected volume data to your graph with an equation and $R^2$ value
6. Calculate the experimental estimate from the slope and number of moles of the gas in the syringe:

$R =$ ____________

7. Compare the expected and experimental slopes (see the example in the Introduction)
8. In your discussion make sure you include:
   - The assessment of your data for accuracy and precision
   - The assessment if your data supports Charles Law
   - Potential sources of experimental error

**Appendix (setting up Excel)**

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 2 | | | | | | | | |
| 3 | | | | Measurements | | Converted measurements | | Calculated volume (L) |
| 4 | p = | 1.00 | atm | T (°C) | V (mL) | T (K) | V (L) | |
| 5 | R = | 8.21E-02 | Latm/molK | 67.0 | 8.0 | 340.0 | 8.0E-03 | 7.96E-03 |
| 6 | n= | 2.86E-04 | mol | 47.0 | 7.5 | 320.0 | 7.5E-03 | 7.53E-03 |
| 7 | $R_{exp}$ = | 7.55E-02 | Latm/molK | 35.0 | 7.3 | 308.0 | 7.3E-03 | 7.27E-03 |
| 8 | %error= | 7.96 | | 21.0 | 6.9 | 294.0 | 6.9E-03 | 6.96E-03 |
| 9 | | | | 5.5 | 6.7 | 278.5 | 6.7E-03 | 6.63E-03 |
| 10 | | | | 0.0 | 6.5 | 273.0 | 6.5E-03 | 6.51E-03 |
| 11 | | | | -6.0 | 6.4 | 267.0 | 6.4E-03 | 6.38E-03 |

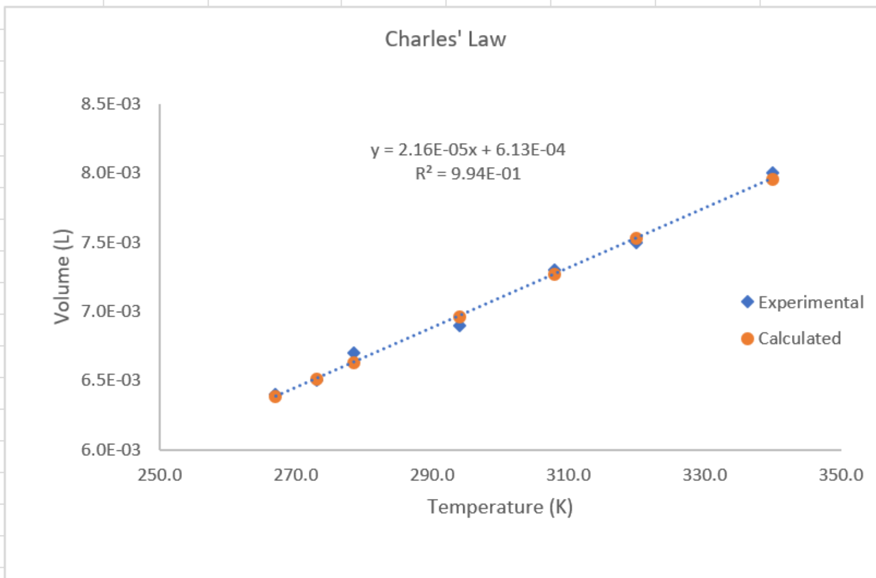



Figure A. The table with data, and the graph with the experimental and calculated values

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 3 | | | | Measurements | | Converted measurements | | Calculated volume (L) |
| 4 | p = | 1 | atm | T (°C) | V (mL) | T (K) | V (L) | |
| 5 | R = | 0.08206 | Latm/molK | 67 | 8 | 340 | =E5/1000 | =0.0000216*F5+0.000613 |
| 6 | n= | =B4*E8/1000/B5/F8 | mol | 47 | 7.5 | 320 | =E6/1000 | =0.0000216*F6+0.000613 |
| 7 | $R_{exp}$ = | =0.0000216/B6 | Latm/molK | 35 | 7.3 | 308 | =E7/1000 | =0.0000216*F7+0.000613 |
| 8 | %error= | =ABS(B5-B7)/B5*100 | | 21 | 6.9 | 294 | =E8/1000 | =0.0000216*F8+0.000613 |
| 9 | | | | 5.5 | 6.7 | 278.5 | =E9/1000 | =0.0000216*F9+0.000613 |
| 10 | | | | 0 | 6.5 | 273 | =E10/1000 | =0.0000216*F10+0.000613 |
| 11 | | | | -6 | 6.4 | 267 | =E11/1000 | =0.0000216*F11+0.000613 |

Figure B. The respective formulae for the calculations

**Pre-Lab Questions**

1. According to Charles' Law, are volume and temperature directly or inversely proportional to one another?

2. How are you going to make sure that the pressure remains constant through the experiment?

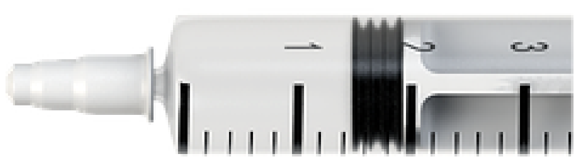
3. Why do you apply silicone grease on the plunger?

4. Assuming there is no experimental error, how would the volume readings change, if at all, if you were placing the syringe in the baths in reverse order (starting with the one with the highest temperature)? Explain.

5. Why do you think you have to cap the syringe?

6. Why do you think you cannot start with a syringe set to 0 mL?

7. What would be the reading with the correct number of significant figures in the syringe shown?



**Post-Lab Questions**

1. If your volume measurements for each temperature were smaller than expected, but they fit on a straight line, would the graph be affected, and if so how? Explain.

2. Would the accuracy and precision be affected in the previous situation, and if so how? Explain.

3. What do you think the reason could be for smaller volume readings than expected?

4. Rearrange the Ideal Gas Law ( $pV = nRT$ ) to show that it supports Charles' Law.

5. Using the rearranged form of the Ideal Gas Law, what is the value of the slope and intercept in terms of variable(s) and constant(s) (not the actual numerical values)?

6. Assume you repeat the experiment with a 60-ml syringe set to 30.0 mL at the beginning. How would the graph look different, if at all? Explain.

7. Assume you repeat the experiment with $CO_2$ instead of air. How would the graph look different, if at all? Explain.