Vacuum Systems for Scientific Modeling

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Abstract

- Many high schools and universities have small vacuum systems which are used primarily for demonstrations. We review here more advanced laboratory applications of vacuum systems that have been developed as part of the annual AVS Science Educator's Workshop*. An emphasis on scientific modeling of exponential processes and non-ideal behavior of gasses can give students a better understanding of real science and engineering.
- We focus on two vacuum system experiments in which we connect theory, model, and observations. The first experiment examines the pump down characteristics of the vacuum system which is predicted to follow an exponential behavior. The second examines Boyle's Law but the data does not obey the ideal gas model allowing discussion of a polytropic model and methods for determining the exponent in the model from experimental data.
- *https://www.avs.org/Education-Outreach/Science-Educators-Workshop

What do you do with your vacuum system ?

- We blow up balloons and marshmallows, freeze or boil water, and show that sound waves need air to propagate…

Fun stuff …
but we could do much more …

Theory – Models - Observation

- **We can use our vacuum chambers to help students understand the connections between theory and models through observation.**
- Theory = fundamental physical principles
- Observation = what we see happening in the lab (which does not always follow the theory)
- Model = Mathematical description of the observations.

Two examples

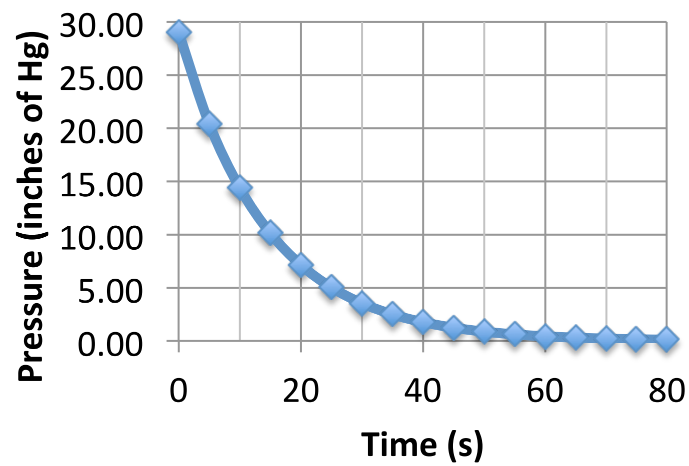
- Exponentials – Using the ideal gas law to model vacuum chamber pressure vs. time when pumping down the chamber.

- Boyle's Law – inflating a balloon in a vacuum system expecting PV = constant … and how to model a different result.

Exponentials

- Exponentials arise when the change in some quantity is proportional to the quantity itself.
  - Often we explore this as a function of time where the change in the quantity also gets bigger if you observe for a longer period of time.
- $\Delta X = C X \Delta t$
  - Where C is some constant
- This is equivalent to $X = X_0 e^{Ct}$
- (For advanced students who have seen calculus, notice $dX/dt = CX$ has a solution $X=X_0 e^{Ct}$.)

Exponentials in Vacuum Pumping

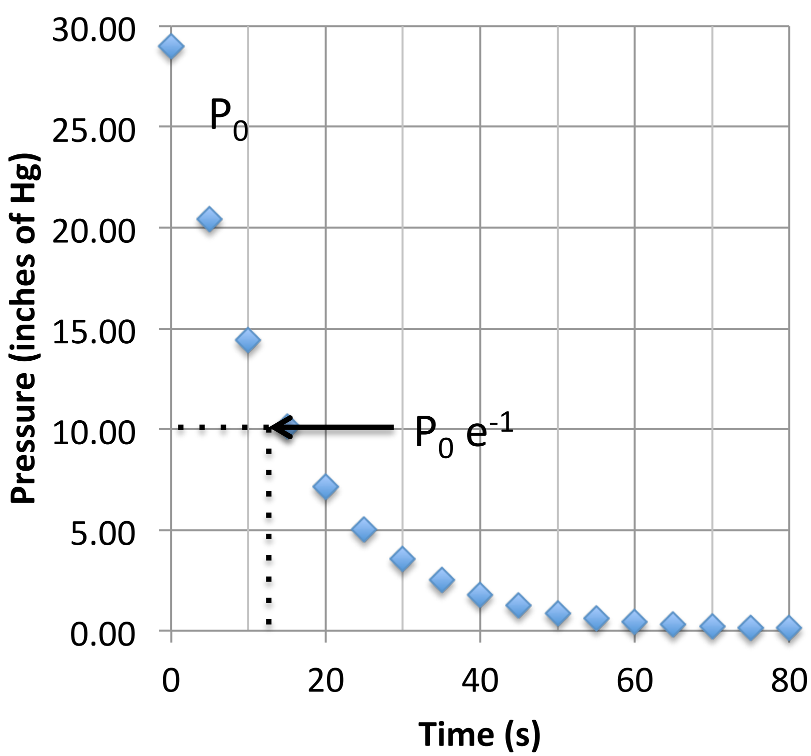


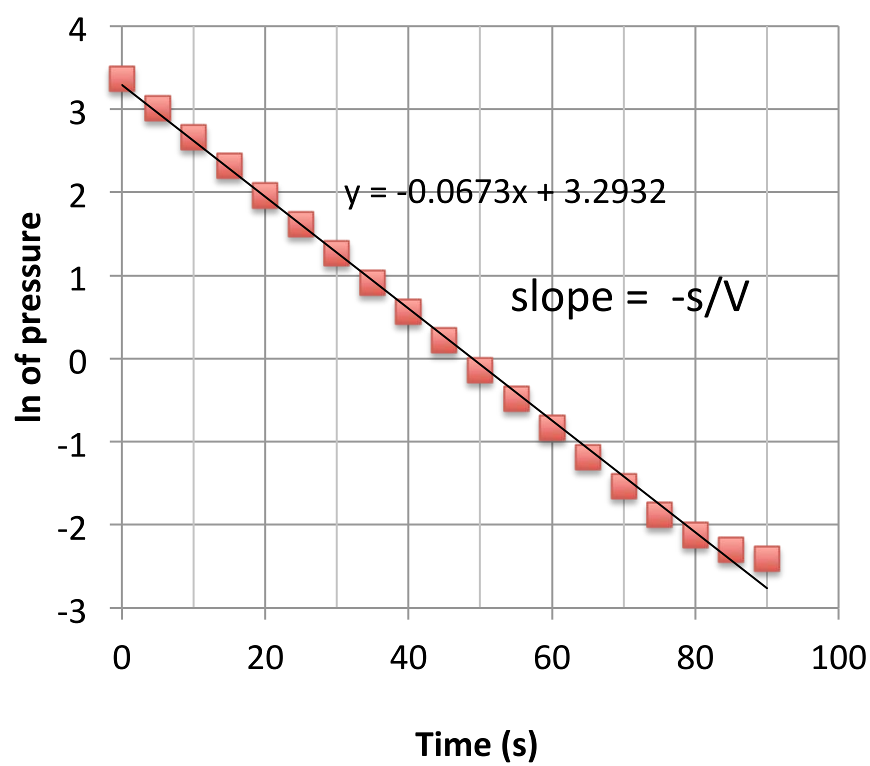
- Vacuum Pump Down
  - As we pump down a vacuum chamber from atmosphere the pressure decreases exponentially.
- Why?
- Start with ideal gas law: PV = NRT
    - P = pressure
    - V = volume
    - N = number of gas molecules (in moles)
    - T = temperature
    - R = Universal Gas Constant

- Change in Number of molecules in the chamber (ΔN) = Number entering – Number leaving
    - Assume Number entering = 0 (no leaks)
    - Assume Number leaving = Number going into pump
- Then $\Delta N_{chamber} = - N_{leaving} = - \Delta N_{pump}$ (1)

- Pumps are often characterized with a pumping speed, s, in liters/s
  - $s = \Delta V/\Delta t = \Delta N_{pump}\,(RT/P) / \Delta t$
  - So $\Delta N_{pump} = Ps\,\Delta t / RT$
- Substituting this into equation (1):
  - $\Delta N_{chamber} = (Ps/RT)\,\Delta t$ (2)
- From the ideal gas law: $\Delta N_{chamber} = (V/RT)\,\Delta P$
  - Since V and T are constant
- Substituting this into equation (2)
  - $(V/RT)\,\Delta P = -(P/RT)\,s\,\Delta t$
  - $\Delta P = -(s/V)\,P\,\Delta t$
- We recognize this as being an exponential form with a solution $P = P_0\,e^{-(s/V)\,t}$

- Students take **pressure vs. time data**
- Plot P vs. t to see the exponential shape
  - Find the pumping speed, s, from the 1/e point
- Plot ln(P) vs t to see a linear plot
  - Find the pumping speed, s, from the slope





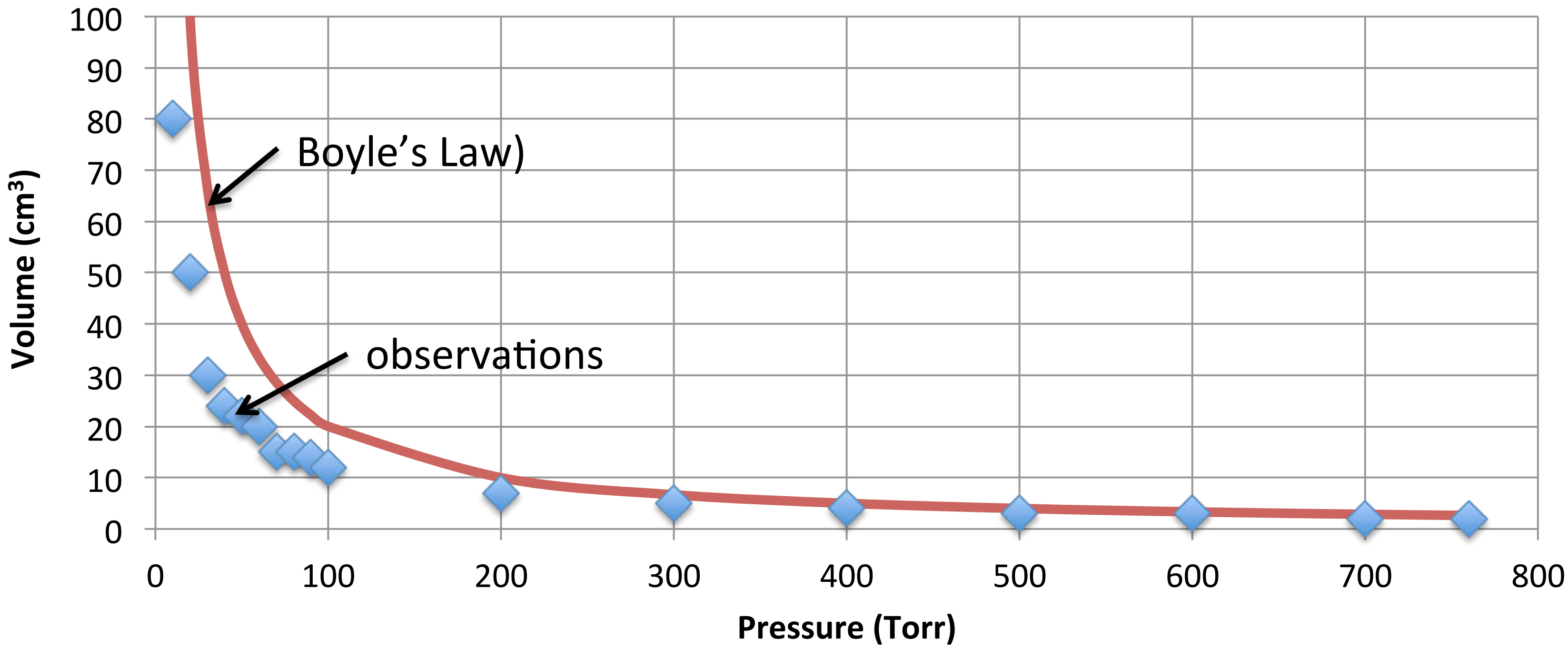
Boyle's Law

- The ideal gas law predicts a very simple relationship for a constant number of gas molecules held at a constant temperature.
- $P_1V_1 = P_2V_2 = NRT$

  => PV = constant

- A sealed, slightly inflated, balloon in a vacuum chamber provides a nice source of constant N.
- As you pump out the chamber (change P), the balloon will expand (change V).

- This raises interesting questions in experimental design.
    - How do we measure the balloon volume inside the chamber?
    - Would a spherical or cylindrical balloon be better?
    - Things change quickly, how do I record data quickly ?
- If you do the experiment carefully, your data will be slightly different from Boyle's Law.



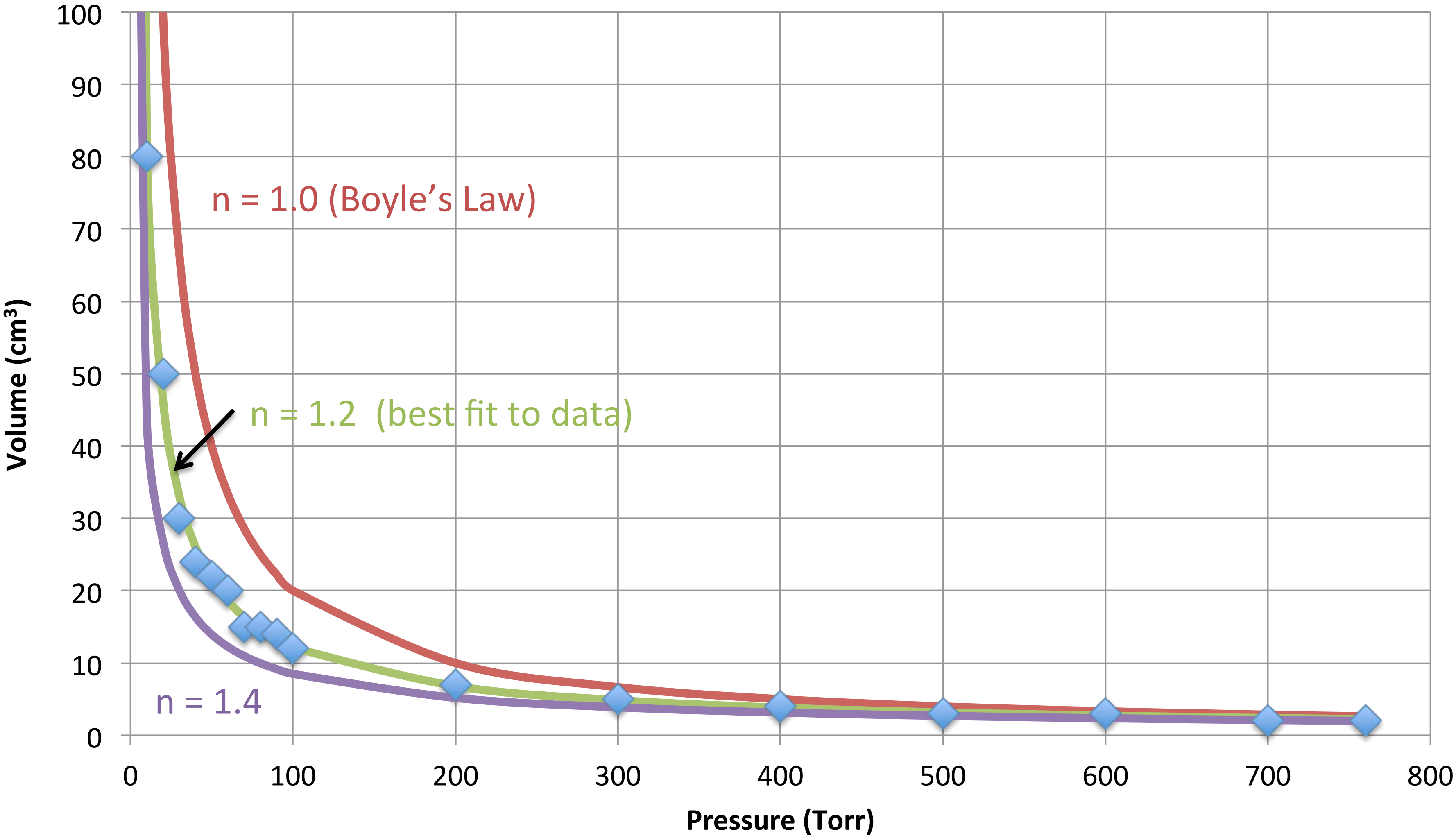
- What do you do now?
  - Blame it on experimental error and move on.
  - Blame it on bad equipment and move on.
  - Use this as an opportunity to develop a model for data that behaves differently from your theory.

Polytropic models

- Notice:
  - If Pressure is constant $P = \text{constant}$
    - » could be written as $PV^0 = \text{constant}$
  - Boyle's Law $PV^1 = \text{constant}$
  - Could gasses obey $PV^n = \text{constant}$??

  - This is an example of a polytropic model.

- Determine what n (not necessarily an integer) would best fit your data.



100
90
80
70
60
50
40
30
20
10
0
Volume (cm³)
0
100
200
300
400
500
600
700
800
Pressure (Torr)
n = 1.0 (Boyle's Law)
n = 1.2 (best fit to data)
n = 1.4

- You now have a mathematical model for your data which does not agree exactly with the theoretical model provided by the ideal gas law.
- Your model, however, gives you a way of working with similar data in a real world environment.

AVS Science Educators' Workshop

- AVS – a professional society whose areas of interest include vacuum science.
- Offers a free 2-day Science Educators' Workshop at their annual meeting each year to a limited number of teachers.
    - 2014: 10-11 November in Baltimore, MD
    - 2015: 19-20 October in San Jose, CA
    - 2016: 7-8 November in Nashville, TN
    - Apply on-line at the web site listed below.
- Experiments discussed here are included in this workshop and described further at:
- https://www.avs.org/Education-Outreach/Science-Educators-Workshop

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