Measuring the Speed of Sound as a Function of Gases

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Abstract

The objective of this experiment is to determine the speed of sound in various gases and compare the experimental findings to known values. Introducing a known gas into a tube, which has been evacuated with a vacuum pressure pump, will provide the conditions necessary to study the speed of sound in the gas. Thermodynamics can also be studied by investigating the relationship between heat capacity and the speed of sound in gases. The misconception concerning the speed of sound pressure will be dispelled as the speed is seen as constant with the gas. However, students will see that the amplitude will change.

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1.0 Theory and Background on the Speed of Sound and Heat Capacities

This experiment focuses on the speed of sound in a controlled pressure environment. Sound is propagated through gases (and other media) by compressional or longitudinal waves. No sound is transmitted in the absence of a media. The sound waves are periodic where the particles vibrate in the same direction as the energy, which disturbed them. The sound waves are periodic where the particles occur in the same direction as the energy. A longitudinal wave appears below (fig. 1) showing points of compressions (c) and rarefactions (r).

    (r)   (c)   (r)   (c)   (r)   (c)   (r)   (c)   (r)
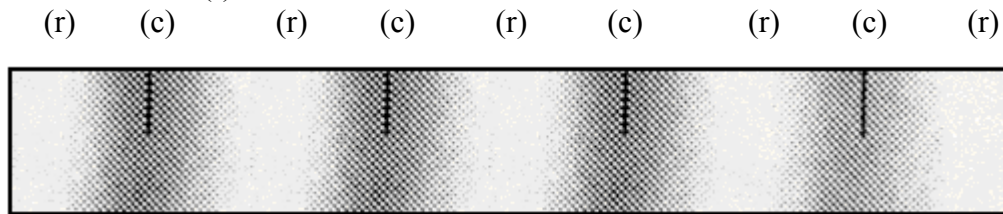

Figure 1

In the experimental method used in this demonstration, a sound is generated at one end of a closed tube. A time of flight method is used where the distance is the length of the tube. The signal from the function generator triggers an oscilloscope and sends a pressure wave down the tube. The difference between the trigger and response wave is the time to travel the distance between the speaker and microphone. The speed of sound is the distance traveled divided by the time required. v_s is the speed of sound, d is the wavelength (length of the tube) and t is the time of flight.

$$v_s = d/t \qquad \text{(Equation 1)}$$

The accepted value for the speed of sound in air (accurate only over a relatively small range of temperatures) can be determined by: $v = (331 + 0.610t)$ m/s where t is the temperature in degrees Celsius.

Thermodynamics can be the focus as relationships of constant-volume and constant-pressure (adiabatic constant when Cp/Cv) are applied to the known information about the system. Students can calculate the theoretical speed of sound with this equation (based on the ideal gas laws) and compare it to accepted values and the results from the demonstration. The relationship between the speed of sound in an ideal gas can be demonstrated by the relationship:

$$v_s = \sqrt{\gamma RT/M} \qquad \text{(equation 2)}$$

v_s=speed of sound
γ=adiabatic constant (Cp/Cv)
R=universal gas constant 8.314J/mol K
T=absolute temperature
M=molecular mass of the gas in kg/mol

If an ideal gas is placed in an insulated cylinder and allow it to expand slowly without heat flow, adiabatic expansion will result.

$$\Delta Q=\Delta E+\Delta W=0 \Rightarrow dE=nC_v dT=-pdV$$

$$pV=nRT \Rightarrow pdV+Vdp=nRdT=n(Cp-Cv)(-pdV/nCv) \Rightarrow$$

$$pdV\left[1+(Cp-Cv)/Cv\right]+Vdp=0 \Rightarrow$$

$$dp/p+(Cp/Cv)(dV/V)=0$$

$$Cp/Cv=\gamma \Rightarrow \ln p+\gamma \ln V=constant \Rightarrow pV^\gamma=Constant$$

The Newton-Laplace equation can be used for the speed of sound in a gas. The experimental value from equation one can be compared to this calculated speed of sound.

$$v_s=\sqrt{\gamma p/\rho} \qquad \text{(equation 3)}$$

v_s=speed of sound
γ=adiabatic constant (Cp/Cv)
p=pressure
ρ=density of the gas

An added value of this setup is to use the speed of sound method to calculate the heat capacity of the gas. This value can be compared to the accepted value of the adiabatic constant. Rearrange equation two:

$$\gamma=v_s^2 M/RT \qquad \text{(equation 4)}$$

γ= adiabatic constant (Cp/Cv)
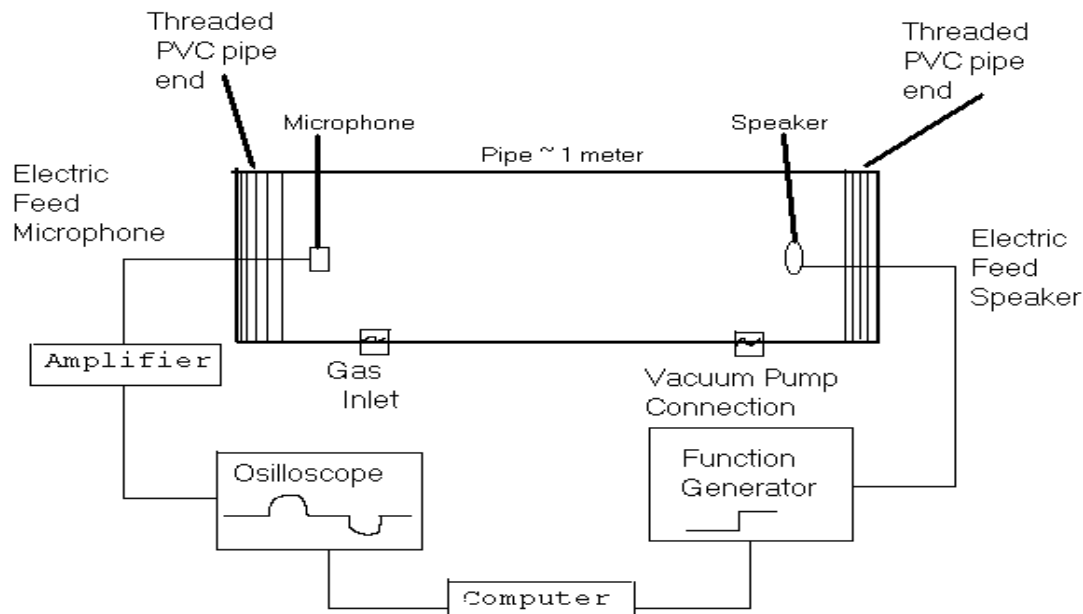v_s=speed of sound
M=molecular mass of the gas in kg/mol
R=universal gas constant 8.314J/mol K
T=absolute temperature

**Note the equations and derivations were obtained from Rana Salameh; see the web site referenced at the end of this paper.

2.0 Description of Experimental Equipment

Experiment Set Up

2.1 Description of Experimental Setup

A PVC pipe of approximately one meter in length and 5 cm in diameter was cut and ports for gas were placed at each end. The ports were placed perpendicular to the tube openings. A pressure gage was fitted opposite the inlet pressure valve. PVC plugs with O-rings were fitted to the ends. The plugs were drilled so that electrical feeds went through the end. Electrical feeds were placed at both ends of the tube. A strong epoxy held the electrical feeds in place and formed a seal.

On the interior of the tube, a microphone was placed at one end and connected to the interior end of the electrical feed. At the other end a speaker was placed and connected to the interior end of the electrical feed. The microphone and speaker were held in place by epoxy.

The microphone I used had an amplifier connected to a plug. The plug of the microphone was connected to channel one of the oscilloscope. The oscilloscope channel two feed was connected to the function generator. The function generator was connected to the external feed of the speaker. The oscilloscope and function generator connect together through a BUS port and then to the printer port of the computer. The computer software was loaded in order to run the computer program.

When the experiment is ready to run, the gas ports are opened and a vacuum moves the air through the tube. The inlet tube is then closed and the pressure is reduced to the desired amount. The vacuum end of the tube is then closed and the gas to be tested is introduced through the inlet valve.

3.0 Experimental Procedure

Procedure Part A:
1. Connect the function generator to the end of the tube that has been fitted with the speaker.
2. Connect the microphone to an amplifier and then the oscilloscope.
3. Connect the PVC pipe to the vacuum pump and reduce the interior air pressure to 1 TORR.
4. Introduce the gas to be tested. Continue to fill until the interior air pressure is 760 TORR and hold this pressure constant.
5. Trigger the function generator to send a sound signal to the speaker. The speaker will trigger the oscilloscope and send a pressure wave down the tube. As the wave passes the microphone a signal will appear on the oscilloscope.
6. Determine the frequency of the signal by finding the time period between the onset of the trigger wave from the function generator and the response wave of the oscilloscope.
7. A time of flight method is used here, so the length of the tube is needed for wavelength calculations. Accurately measure the distance between the microphone and the speaker.
8. Use these measurements to calculate the speed of sound in the gas. The speed of sound can then be used to find the heat capacity for the gas.
9. Repeat the experiment for various gases. Gases that are safe and easy to procure are: Helium, Argon, Carbon Dioxide.


Procedure Part B:
1. Repeat the setup procedure above.
2. After the gas has been tested at 760 TORR, reduce the pressure to 380 TORR and 10 TORR.
3. Observe that the speed of sound remains constant for the gases (ideal). The amplitude does diminish until the pressure is reduced to the point that there is no longer a medium for sound to travel.

4.0 Experimental Results

The conditions of the testing for air were 760 TORR and 20 degrees Celsius. The trigger signal is quite clear. The onset of the response is clear, however there is a bit of attenuation.
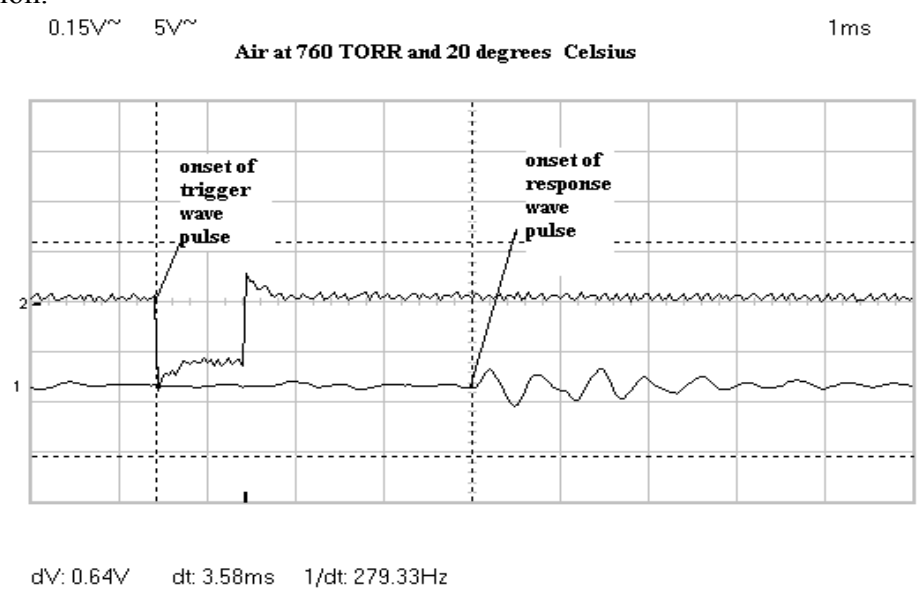
The conditions for the testing in this run for helium were 760 TORR and 20 degrees Celsius. The trigger signal is quite clear and the response signal onset is easy to determine. The data was taken in the first of a run after air was removed and helium introduced.
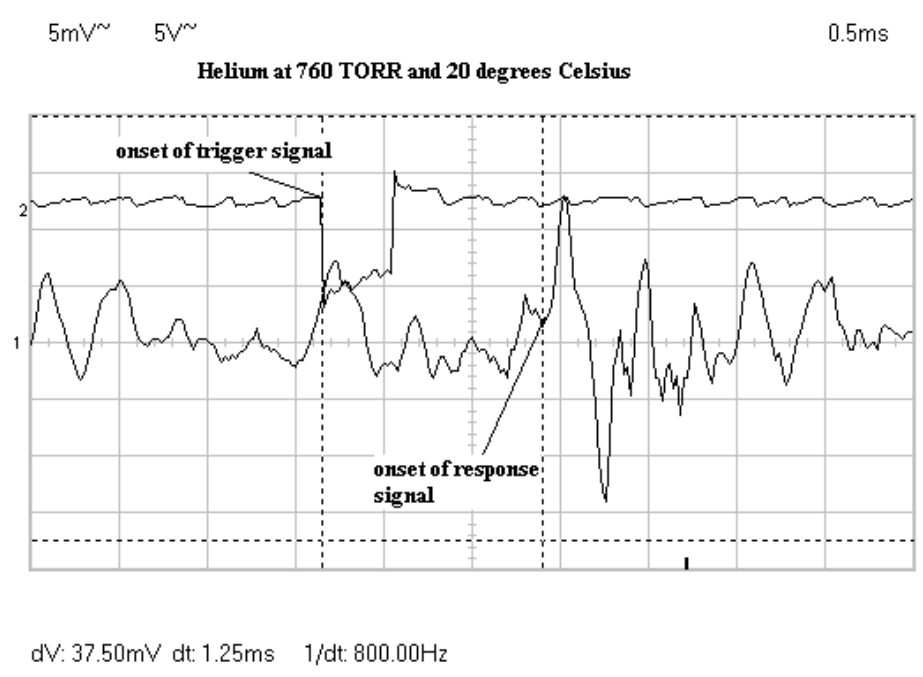
The conditions for this argon run were 760 TORR and 20 degrees Celsius.   No apparent problems with this run.

50mV~   5V~   0.5ms

Argon 760 TORR and 20 degrees Celsius

onset of trigger wave
pulse

onset of
response wave
pulse
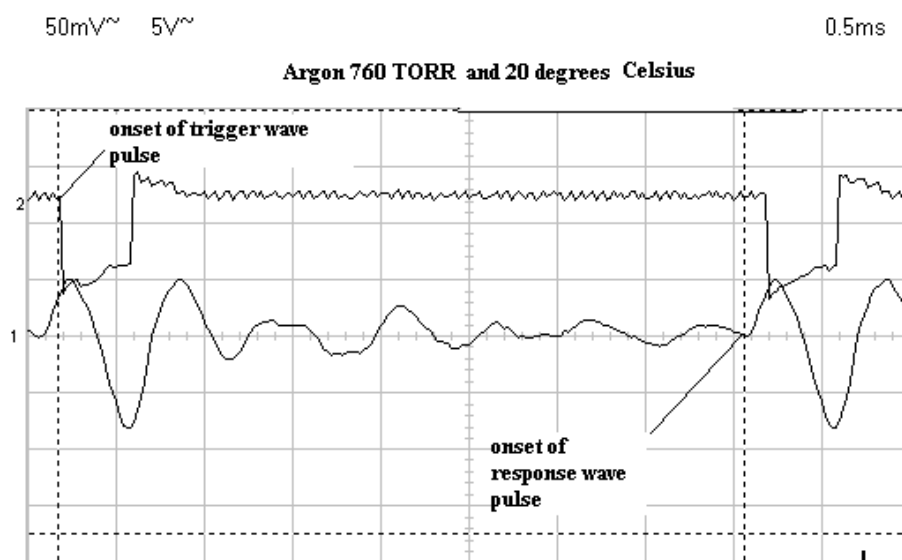
dV: 375.00mVdt: 3.89ms   1/dt: 257.07Hz

5.0 Calculated Data Tables and Sample Calculations

The equation used for the information in Data chart 1 is: $v_s = d/t$.

Data chart 1 (see equation 1)

Gas	Time (s)	Distance (m)	Velocity $v_s = d/t$ (m/s)	Value from literature (m/s)	Percent error
Air	0.00358	1.20	335	343	2.3%
Helium	0.00125	1.20	960	1007	4.7%
Argon	0.00389	1.20	308	321	4.1%

The equation used for the information in Data chart 2 is: $\gamma = v_s^2 M/RT$

Data chart 2 (see equation 4)

Gas	v_s m/s	v_s^2 m²/s²	M Kg/mol	R J/mol K	T K	Experimental γ	γ from literature	Percent Error
Air	335	112,000	0.02895	8.314	293.15	1.33	1.4	5.0%
Helium	960	922000	0.004	8.314	293.15	1.51	1.67	9.4%
Argon	308	94,900	0.039948	8.314	293.15	1.56	1.67	6.6%

6.0   Conclusion

The conclusion of this experiment is that the speed of sound can be determined for various gases using the experimental setup described. The results came within a range of 2.3 to 4.1 percent error from accepted values in literature. The determination of heat capacity is also possible with this apparatus, however the experimenter needs to be more aware of subtle changes in temperature, which may occur during the experimental testing time. The values for heat capacity were between 5.0% and 9.4%.

7.0 Safety notes

It is important to stress safety in this experiment. Safety goggles should be worn at all times. The electrical connections must be securely insulated from the outside. The tube is to be reduced to a low pressure, which could pose a danger of implosion. Be sure to allow the pressure to return to 760 TORR when not in use. Extreme caution should be used when dealing with pressurized gases. Safety goggles should be worn at all times as a precaution. When applying sealant and paint, work in a well-ventilated area. The PVC pipe should be cut with caution, sand edges to reduce chance of wear on the connection wires. All of the compressed cylinders should have regulators of 1 PSI above atmospheric pressure.

8.0 Possible sources of error

Throughout this experiment, I found the following to be areas that needed special attention in terms of error.
1. The tube has resonance feature inherent in the length of the tube. Avoid frequencies that maximize this interference.
2. The sound does bounce back inside of the tube due to reflection. This will cause extra waveforms in the returned signal. Be careful to minimize this factor by insulating the microphone from as much interference as possible.
3. From an electronic point of view, there are phase delays due to the features of the microphones and speakers. Select higher quality materials to reduce phase delays.

9.0 Equipment Cost

Item	Supplier	Cost
Robinair 15600 vacuum pump	Network Tool Warehouse	$300.00
Velleman PC Oscilloscope 50MHz (PCS500)	Quality kits	$360.00
Velleman PC Function Generator Kit (K8016)	Quality kits	$140.00
Piezo Microphone element (#423-1003-ND)	DigiKey	$50.00
Speaker Element (#423-1036-ND)	DigiKey	$15.00
PVC pipe, Connections, tubing	Lowes hardware	$45.00
Misc. wire, resistors, soldering iron, computer connection cables, adapters	Radio Shack	$150.00
**Various gases with canisters, can be rented –use the correct regulator $7.00 per cylinder	Local distributor	$30.00
Batteries, Paint	Meijer	$20.00
	Total cost	$1,110

**Please note that the cost of gases was included for information purposes. James Solomon through the University of Dayton at Wright Patterson Air Force Base provided the gases from the gas pressure tanks in his laboratories. Also, James Solomon provided O-rings, pressure valves and wires from the labs at Wright Patterson Air Force Base.

10.0 References

Giancoli, Douglas C. *Physcis: principles with applications (fifth edition).* New Jersey 1998.

Holmes, Brian W. "Acoustics Demonstration Tube". *The Physics Teacher* May 1986:287-288.

Nave, R. Sound Speed in Gases. February 2002. http://hyperphysics.phy-astr.gsu.edu/hbase/sound/souspe3.html

Salameh, Rana. Heat Capacity Ratios: Sound Velocity Methods. September 1999. http://inst.augie.edu/~rsalameh/expla.html

Acknowledgements

Personal notes

From the onset of this project, I was convinced that this was a very simple set up, which would supply clear concise results. However, as with any physics demonstration many variables added to the construction problems of the apparatus. Initially, I planned to purchase a function generator and oscilloscope that were freestanding traditional equipment. I was advised that moving into the twenty first century would be wise, and the computer equipment would have the added benefit of wide screen projection by a computer device. This does allow for greater vision and resolution for demonstration purposes. The pc oscilloscope and function generator came from Velleman products, but the function generator came as a kit. The function generator came in 500 pieces with 954 solder points. The kit went together nicely and after a software issue was resolved, the computer equipment worked well.

The second selection was of the microphone and speaker. After several trials of microphone types I found the most reliable connection came from a Radio Shack version of a lapel clip microphone fitted with adapters to attach to the oscilloscope. The speaker should be of high enough quality to transmit the sound the distance of the tube. The speaker was purchased from an electronic supply house since the speaker types from local vendors did not have enough amplification.

The other variable piece was the tube. I originally selected a two-meter length, but practicality of size changed this. In fact, a tube less than one meter would work just as well. Care must be taken in the construction so that a vacuum seal can be reliable. I also found that great care must be taken in the types of adhesive used inside the tube. The safest and least likely to emit gases or produce leaks was a super glue type adhesive.

Once all the issues were resolved, the project was indeed a simple one as the data was easy to measure and analyze. The results were consistent and within a reasonable error. I have freshmen in a physical science class, so I will be using this demonstration for them. Since their level of understanding of ideal gases is limited, the main issue will be the speed of sound in the gas. I did provide the extra information about adiabatic constants and ideal gases in order to appeal to the more chemistry and physics students who may later appreciate the value of this information. In fact, I have shared this with our physics teacher and the possibility of use in the higher-level courses would be welcomed.

Sample Questions:

1. Why does the voice change when helium is introduced to the human system?

2. A saxophone player has a change in sound as they reach the end of a long note. Explain what may cause this phenomenon.

3. How could this demonstration be used to determine the type of gas in the chamber?

4. How far above the earth would you have to go to in order to not hear a sound?

5. Use this demonstration apparatus to develop an experiment, which proves the speed of sound in ideal gases is independent of pressure.

6. Develop an experiment to slow the speed of sound in air to 1 m/s.