Vacuum Bazooka – Extended

Aleš Mohorič

FMF, University of Ljubljana, Ljubljana, Slovenia,
ales.mohoric@fmf.uni-lj.si

"Vacuum bazooka" is a simple and amusing experiment, which easily catches the attention of students. With a few very basic steps a lot of physics can be covered. We have extended the analysis by employing pressure sensors at the nozzle and at the centre of the tube. Some interesting results follow from the measurements.

Introduction

A vacuum cannon is a simple and amusing device which easily catches the attention of students. With a few very basic steps a lot of physics can be covered [1]. We have extended the analysis by employing pressure sensors at the nozzle and the centre of the pipe. Some interesting results follow from the measurements.

In a cannon the pressure of exploding gas forces the projectile down the barrel whereas in the vacuum bazooka the vacuum sucks (or is it the atmospheric pressure, that pushes?) it in and the projectile flies out on the other side. The bazooka can be constructed from a plastic pipe (Fig. 1) and a corresponding T-section of a suitable diameter (~ 4 cm). A length of one or two meters suffices. A vacuum cleaner or pump is connected to the T-section. The projectile must have a circular cross-section and appropriate diameter. Suitable objects are pink-ponk balls or photograph film cartridges. First step in the experiment is to create under pressure in the pipe by the vacuum pump. Once the pump is turned on, the nozzle is sealed with a piece of paper (cardboard) or aluminum foil which must be strong enough to withstand the pressure difference. The under pressure will keep the seal in place. The other side of the pipe is sealed by the projectile which can be held by hand. Once the projectile is released it will shoot down the pipe and exit at the other end.

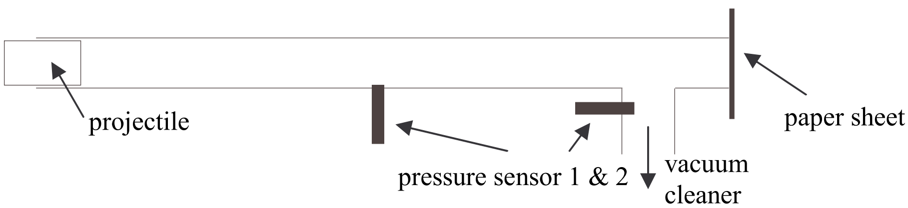

Figure 1: Vacuum bazooka is constructed from a straight circular pipe and a T-section at one end. A vacuum cleaner is attached to the outlet of the T-section thus leaving a straight path for a projectile and enabling the vacuum pump to produce sufficient under pressure. Pressure sensors (they are not essential for the bazooka functionality, their role will be explained later) are mounted on the bicycle tire valves and located in the middle and at the end of the pipe.

A qualitative analysis of the bazooka can start with a demonstrational shot. It is interesting how puzzling the cause of the force on the projectile can be for students. It is hard for them to imagine, why the projectile is not sucked in the vacuum cleaner, especially if it is running during the shot. The force is the result of pressure differences between the atmosphere and the inside of the pipe. When the projectile passes the T-section, the net force will still push it towards the nozzle until it breaks the seal and after that only drag will slow it down. The force on the projectile is independent of its mass. An interesting experiment is to use two projectiles that have the same shape but different mass (some play dough in a film cartridge will do). The students are stimulated to predict for both projectiles (l – light, h – heavy) the

- force accelerating them ($F_l = F_h$),
- time spent in the pipe ($t_l < t_h$),
- final speed ($v_l > v_h$),
- acceleration ($a_l > a_h$),
- kinetic energy ($W_{kl} = W_{kh}$), and
- linear momentum ($G_l < G_h$).

Students should explain their reasoning!
Many students will use the "formula" to find this relations, but it is important to encourage them to use simple reasoning and fundamental laws to come to the conclusion. For instance: since only the cross-section and pressure difference determine the force, both forces must be equal. If the forces are equal, the lighter projectile will have greater acceleration. If the acceleration is greater, the time spent inside the tube will be shorter. The change in linear momentum is given by the force impulse and clearly the lighter projectile will have smaller momentum. The change in the kinetic energy is given by the work of the force along the length of the pipe which is equal for both cases. In this way, qualitative analysis builds conceptual understanding.

After the qualitative treatment has been completed the quantitative analysis of the problem can follow. In the first approximation the vacuum bazooka can be treated like this: constant pressure difference Δp exerts constant force on a projectile along a fixed path with the length l. The speed of the projectile of mass m and cross-section S at the end of the pipe is:

$$v = \sqrt{\frac{2\,\Delta p\, S\, l}{m}}\ . \qquad (1)$$

This can be easily tested by measuring the nozzle speed and pressure inside the pipe. For this purpose we used Vernier interface [2], photogates and pressure sensor. Precaution is needed because the projectile kinetic energy may be substantial and for this reason the nozzle must be pointed away from the students. The photogates must be positioned in such a way that the piece of paper, that seals the pipe, does not obstruct the measurement.

Experiment

As an example a projectile with mass of 30 g, pipe with 10 cm^2 cross-section and 1.5 m length were used. Students are encouraged to give an estimate of the pressure difference. Clear upper and lower limits are 1 atm and 0 respectively. Usually the pressure difference is overestimated by almost an order. For a measured pressure difference of 10 kPa the speed of 30 m/s follows from Eq. 1. In our case we measured the speed of 20 m/s It turns out that the approximation does not predict the measured result. Students are stimulated to give the reasons why. Usually the reasons they give are friction and air-leak between the projectile and the walls of the pipe. Only after their attention is turned to the large x (infinite pipe) limit of Eq. 1 they realize a fundamental flaw in the approximation: there is no limit to the speed as long as the pipe is long enough. This is another brain teaser for the students. Usually they are able to set the upper limit for the nozzle speed based on the relativistic effects and only after a guided reasoning to at most the speed of sound.

In a better approximation the acceleration of air that is sucked in the pipe behind the projectile, as it speeds along the pipe, can be taken into account. In this case the second Newton law can be expressed with the coordinate x of the projectile measured from the beginning of the pipe as:

$$\Delta p\, S = \frac{d(m+\rho S x)v}{dt},$$

where ρ is air density. After a few algebraic steps the expression for the speed as a function of the position inside the pipe (the nozzle velocity equals $v(x=l)$) follows as:

$$v = \sqrt{\frac{\Delta p}{\rho}}\,\frac{\sqrt{x^2 + \frac{2mx}{\rho S}}}{x + \frac{m}{\rho S}},$$

which has the upper limit smaller than the speed of sound. The relation can be tested by drilling several holes across the pipe and measuring speed with photogates. The holes must be sealed with transparent tape to keep the pressure unaltered. It turns out, that the last expression (shown in Fig. 2) sufficiently describes the measurements.

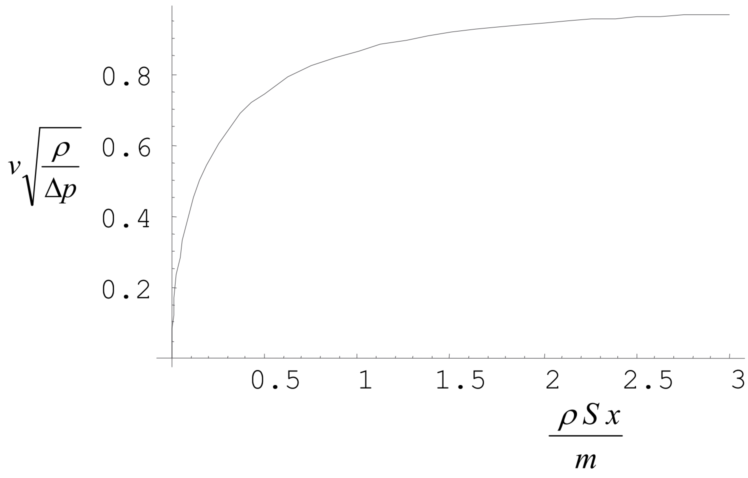

Figure 2: Theoretical speed of the projectile as a function of the position in the pipe.

Further challenge is to find the mass of the projectile for which the range of the bazooka is the largest. Obviously a lighter projectile has a higher nozzle speed than the heavier but is more affected by air drag. This is an experimental challenge. Students can repeat measurements while they add clay or other suitable ballast to the projectile. The theoretical solution to this problem is beyond the scope of this paper although several quantities can easily be obtained. For instance, it can be shown that the kinetic energy of the projectile in the limit of large mass equals the energy required to evacuate air from the pipe in the first place:

$$\lim_{m\to\infty} \tfrac{1}{2} m v^2 = \Delta p\, S\, l\,.$$

We extended the experiment by measuring pressure at two positions: in the middle of the pipe and near the nozzle. The pressure sensor from the Vernier set of sensors was used. The sensor is connected to the pipe by a hollow tube – we used tubes from modified bicycle valves.

Firstly the measurement gives Δp and secondly, the pressure can be followed in time (Fig. 3). It is apparent how the pressure drops as the pipe is sealed and how it rises as the projectile speeds past the pressure sensor.

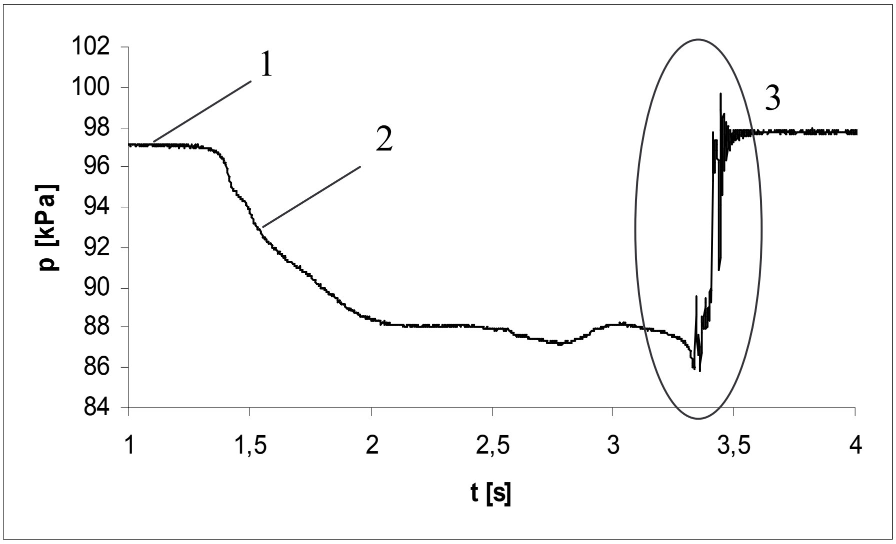

Figure 3: Pressure in the pipe as a function of time. First and second drop in the pressure (marked 1 in the graph) are too small to be observable at this scale. They correspond to the start of pumping and the sealing of the one end of the pipe. With these values it is possible to evaluate the rate at which air is pumped by the vacuum pump using the Bernoulli equation. The third drop in pressure (marked 2) occurs when the other end of the pipe is sealed off by the projectile held in hand. Because the seal is not tight, the pressure in the pipe is changing. After the projectile is released, the pressure jumps back to normal air pressure (mark 3). The encircled part of the graph is represented in Fig. 4.

From the pressure jumps at the first and the second sensor (Fig. 4) the average speed in the last half of the pipe can be determined. Interesting feature is apparent in the pressure graph of the sensor located in the middle of the pipe: the oscillations, that occur after the projectile leaves the pipe, correspond to the sound oscillations of the first harmonic. The length of the pipe is 1.5 m with the first harmonic at frequency $\nu = c/4l = 110$ Hz. This gives the period of oscillation of 0.01 s in agreement with the measured oscillation time.

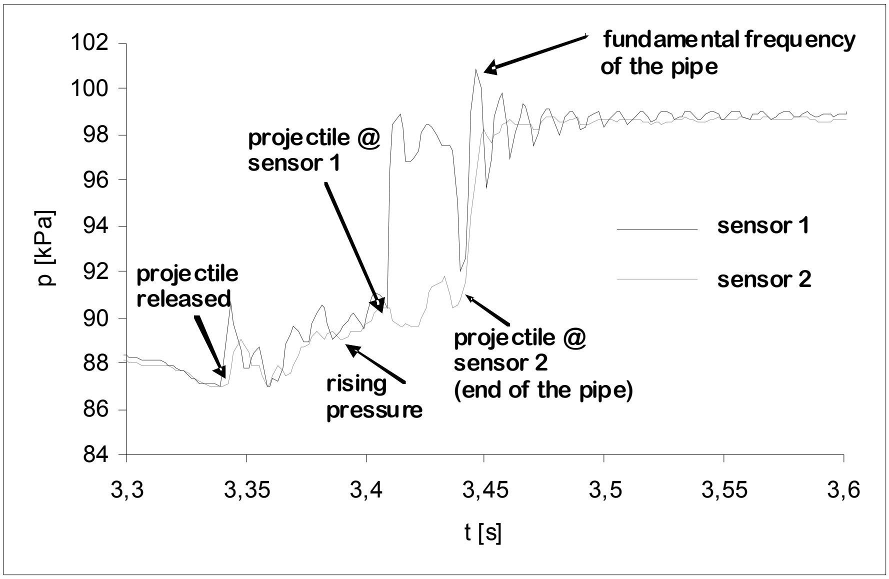

Figure 4: Pressure in the pipe: sensor 1 – measured in the middle, sensor 2 – measured at the nozzle. The moment when the projectile is released can be clearly distinguished. From then on, the pressure in front of the projectile starts to rise, since the vacuum pump is not able to sustain a constant pressure difference. As the projectile passes the sensor, the pressure returns to the atmospheric pressure. After the projectile leaves the pipe, small under pressure starts the first harmonic oscillations, that can also be heard by ear as a short resound. The period 0.01 s of the oscillations correspond to the first harmonic for the pipe of 1.5 m length.

Summary

The didactical benefit of this experiment is its ease in getting the attention, it is fun and involves experimental and theoretical contributions from students. It demonstrates second Newton's law, conservation of energy, the force of the atmospheric pressure, and harmonic oscillations. The qualitative treatment of the problem is very important and rewarding. It helps building conceptual understanding and all predictions can easily be verified during the experiment. In order to execute the experiment the following experimental devices are recommended: computer interface with sensors (such as Vernier interface), LabPro, photogates, scale and pressure sensor. From the theoretical standpoint it involves solving simple differential equation, which is on the undergraduate but above secondary school level.

References

[1] Ayars E, Buchholtz L 2004 Analysis of the vacuum cannon, *Am. J. Phys*. **72** (7) 961 – 963
[2] Vernier Software and Hardware at www.vernier.com