Spark Ignition of Combustible Vapor in a Plastic Bottle as a Demonstration of Rocket Propulsion

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I report an innovation that provides a compelling demonstration of rocket propulsion, appropriate for students of physics and other physical sciences. An electrical spark is initiated from a distance to cause the deflagration of a combustible vapor mixed with air in a lightweight plastic bottle that is consequently propelled as a rocket by the release of combustion products, i.e., a "whoosh rocket." My recommendation is that the standard fuel for pedagogical whoosh demonstrations be isopropanol, and the recommended vessel is the 3.8-L HDPE bottle.

Development of this demonstration was inspired by witnessing a "whoosh bottle demonstration"[1] in the fall of 2005 at a meeting of the North Carolina Section of the AAPT. This featured the combustion of 10 ml of methanol in a 5-gal (19-L) polycarbonate water dispenser bottle upon ignition with a match. It is called the "whoosh bottle demonstration" because of the sound made during the resulting deflagration.

There have been reports of accidents that have occurred while using methanol for this demonstration (with serious student burns in at least one case[2-5]). It is now frequently recommended that it be done only with isopropyl alcohol (isopropanol),[6,7] although ethanol is still suggested.[8] The attachment of wheels to a "whoosh bottle" has been demonstrated,[9] as well as the deflagration of alcohol vapor in a PET bottle to create a rocket[10-12] (with ignition by flame).

Fig. 1. Left, a 19-L polycarbonate bottle in its launch base with wires connecting voltage source shown at bottom left. Right, close-up photo of this launch base. It was formed from two pieces of 3.8-cm thick wood. Top piece has a 5.7-cm diameter hole drilled in it to stabilize the neck of the inverted bottle. The top of the bottle should fit snugly into this hole without being constrained. Two #14 insulated copper wires are routed from each end of the base to the bottom, and then up into what will be the interior of the bottle to form a ~2-mm spark gap.

I invert the 19-L whoosh bottle to form a "whoosh rocket." During its brief powered flight, it emits the same "whoosh" sound as the whoosh bottle demonstration. I have observed it to reach an altitude of ~25 m. Remote initiation of ignition by spark ignition makes it possible to do this safely. The demonstration is even safer when using a smaller vessel, a modern 1-gal (3.8-L) high-density polyethylene (HDPE) bottle (used to sell milk and other beverages). It has walls that are typically 0.5 mm thick and a typical empty mass of 54 g (the 19-L polycarbonate bottle has walls that are typically 1.4 mm thick and a typical empty mass of 730 g).

Safety requires the use of a thin plastic vessel, remote initiation of ignition, and vigilant management of fuel to strictly avoid any substantial pooling as a liquid (outside of a small supply bottle) or dense vapors (outside of the volume used for the combustion demonstration). It is possible for the plastic bottle to rupture during either demonstration, so both ear and eye protection should be used by the demonstrator. Spectators should be at least 10 m from the combustion site.

Implementation

Spark ignition brings valuable benefits to both the established whoosh bottle demonstration and the whoosh rocket demonstration described here, which I refer to collectively as "whoosh demonstrations." The most important benefit is the provision of substantial distance between the demonstrator and the site of combustion. It also allows a vapor mixture to be confined in the bottle prior to combustion, and thus retained for a substantial interval of time (even if the mixture is lighter than air, or heavier than air with the bottle inverted).

An appropriate source of high voltage for the spark is an ignition "starter" manufactured for gas-fueled barbecue grills. I recommend the "electronic" version, shown in Figs. 1 and 2, which uses a 1.5-V dry cell.[13] I find that an acceptable spark is thus formed at the far end of a pair of insulated wires of 3.5 m length. This has been used for upright bottles for the whoosh bottle demonstration (with both 3.8-L HDPE bottles and 19-L polycarbonate bottles), with the configuration shown in Fig. 3. The base shown in Fig. 1 has been used to launch inverted 19-L bottles. The base shown in Fig. 2 has been used to launch inverted 3.8-L bottles.

My development of whoosh demonstrations has benefitted from the availability of a planetarium at Fayetteville State University (FSU), which I've used for launching 3.8-L bottles. It features a robust steel dome that is ~9 m high in the center with an array of ~2-mm holes covering the entire dome surface that strongly attenuates sound. This venue also provides

Fig. 2. Left, a 3.8-L HDPE bottle in its launch base with wires connecting the voltage source that appears below. Right top, photo of the top of this launch base. It was formed from two pieces of 3.8-cm thick wood glued together. A 3.5-cm diameter hole is drilled in it to stabilize the neck of the inverted bottle. The top of the bottle should fit snugly into this hole without being constrained. Two #14 insulated copper wires are routed from each side of the base to the bottom, and then up into what will be the interior of the bottle to form a ~2-mm spark gap. Right bottom, photo of the bottom of this launch base. The wires have been glued into their holes for stability. Plywood has been glued to each side to provide stability for the base. The hole between the wires drains any excess liquid alcohol from the combustion volume prior to ignition.

substantial versatility in lighting. Effective but dim lighting is thus readily available to highlight whoosh demonstrations that feature interesting flame both internal and external to the bottle. I find this especially captivating for a flying bottle. Translucent 3.8-L HDPE bottles are thus preferred over opaque bottles.

I have also launched 3.8-L bottles in a classroom with a conventional ~3 m ceiling. For this, I positioned the bottles prior to launch in an "artillery" configuration, ~0.8 m above the floor and inclined upward by ~20°. A range of ~12 m was observed.

I launch 19-L whoosh rockets outdoors. For this, my students are mentored in the use of trigonometry to determine apogee altitudes. Measurements are made with the Estes Rocket "Altitrak" Altitude Finder.[14] The 3.8-L bottles have been observed to obtain altitudes of ~8 m, and the 19-L bottles altitudes of ~25 m. Most people (scientists as well as nonscientists) find these flights impressive. I provide links to video of these launches in an online appendix.[15] The velocity of fall is slow enough that the bottles can safely be caught by an alert demonstrator or a student, which is recommended for the 19-L bottles if they are likely to otherwise land on concrete, which can fracture them. The temperature of both

Fig. 3. Left, a 19-L polycarbonate water dispenser bottle to be used for the whoosh bottle demonstration in the FSU Planetarium. An ignition cable extends 21 cm into the bottle. Alligator clips are used to attach longer wires to the cable sheath and central conductor at the top. The cable passes through a hole in a 6-cm square plate of plywood that was glued to the cable and rests on top of the bottle. This plate will contain a mixture lighter than air for a limited time, but does not significantly hinder the release of combustion induced pressure. The same cable can be used with 3.8-L bottles. Right, spark gap at the bottom of the ignition cable (fabricated from RG-59/U coaxial cable). The outer copper sheath of the cable was gathered into a 2-mm diameter cylinder, soldered together, and glued to the insulating sheath with cyanoacrylic adhesive to form a robust 2-mm wide and 7-mm long spark gap with the protruding inner conductor.

types of bottles upon landing is observed to be distinctly warm to the touch, but less than ~50 °C.

The suitability of a specific alcohol for a whoosh demonstration depends on the temperature at which it will be performed because of the temperature dependence of the vapor pressure. Isopropanol is preferred for these demonstrations because it burns as a liquid with a yellow flame, which is more readily seen if pooled alcohol is inadvertently burning. Also, it burns slower as a vapor than other alcohols, making it less likely to rupture a plastic bottle. However, an ambient temperature of 21 °C or higher is required for its partial pressure to be sufficient for ignition. Fuels for use at lower temperature are discussed in the online appendix.[15]

To fuel these bottles with alcohol (isopropanol, methanol, or ethanol) for a whoosh demonstration (either rocket or bottle), I add 3 ml of liquid alcohol to the 3.8-L bottles and 10 ml to the 19-L bottles. The demonstration and supply bottles are then capped. The demonstration bottle is tilted and rotated for ~1 minute to spread the liquid alcohol on the interior surfaces while evaporation proceeds. Any excess liquid is then poured out quickly (because the vapor is heavier than air) onto a surface where a very small amount of the alcohol can evaporate without harm or danger. The bottle is recapped. The stoichiometric amount of fluid for a 3.8-L bottle is 0.56 ml of isopropanol, 0.81 ml of methanol, or 0.62 ml of ethanol.

For a vertical launch, the launch base should be fitted to the bottle in the upright position, since alcohol vapor is heavier than air. The base and the fitted bottle are then inverted together. After ascertaining that the launch range is clear of spectators within 10 m of the site of combustion, and that the demonstrator is equipped with eye and ear protection, the ignition wires are attached to the base. I typically initiate launch after counting down 3,2,1, with spark at zero. Several hours need to elapse after ignition before the combustion products are replaced by sufficient air through diffusion to reignite.

Results and interpretation

I provide video recordings online[15] of whoosh demonstrations with 19-L and 3.8-L bottles using the liquid fuels discussed above.

Fortuitously, both the 19-L and 3.8-L whoosh rockets described above are observed to be semi-stable in their directional orientation during powered flight. This is not expected since the center of pressure is expected to be in front of the center of gravity for both types of bottles. Indeed, both types of bottles are observed to tumble while falling down after powered flight ends. It is expected that quasi-stability during powered flight results from a small difference in the positions of these two centers combined with a short duration of powered flight (not more than ~1 s). Thus it is expected that deviation from vertical flight will indeed result in a torque that acts to increase the directional deviation, but the magnitude of this torque is insufficient for a substantial deviation to develop during the duration of powered flight. Detailed aerodynamic calculations and comparison to careful observations might be of substantial educational value within an aeronautical engineering program.

If the fuel/air mixtures described above were ignited in a sealed container of sufficient strength, under adiabatic conditions, the deflagration would cause the post-combustion gas mixture to have the isochoric flame temperature, resulting in a pressure of ~8 atm.[16] This is far more than thin plastic bottles can contain. Thus, if the demonstration does not provide for a sufficiently rapid venting of combustion products, bottle rupture will occur. I have occasionally witnessed bottle rupture during the whoosh rocket demonstration using methanol (see the online appendix[15]). Thin plastic bottles have been observed to be loud but not dangerous.

The term "whoosh rocket" has been used to describe rockets formed from inverted PET bottles (manufactured for carbonated beverages) with volumes of 1, 1.5, or 2 L, fueled as described above with alcohol and ignited by a flame brought close to an opening bored in the bottle cap. The implementation by the Royal Chemistry Society[10] specifies the use of 1- or 1.5-L bottles with a 5-mm hole in the bottle cap, ethanol as fuel, and launch at a ~20° elevation using a ~1-m piece of "guttering" to initially direct the rocket. The implementation by NASA's Glen Research Center[11] specifies the use of 2-L bottles with a 3/8-in (9.5-mm) hole in the bottle cap, isopropanol as fuel, and use of a model rocket launch base with the launch rod going through a hollow cylinder fastened to the bottle to initially direct the rocket upward. The implementation by the Scottish Schools Education Research Centre[12] specifies 2-L bottles, a 5–6-mm hole in the bottle cap, methanol as fuel, and the use of a taut wire to continuously guide the rocket horizontally.

I have launched 2-L PET bottles (with a 9-mm hole drilled in the bottle cap) vertically using the base shown in Fig. 2. The hole in the cap fits over the electrodes shown in Fig. 2 to provide for spark ignition from a distance. The spout of a 3-8-L HDPE bottle was first placed in the hole in the base (after cutting away the HDPE bottle bottom) to hold the 2-L bottle in an inverted position until launch. I did this with the following fuels: methanol (2 ml), ethanol (2 ml), isopropanol (2 ml), and diethyl ether (0.35 ml). All of these fuels provided similar flights to an altitude of ~12 m at a temperature of ~22 °C. These 2-L bottles appear to be less stable in orientation during flight than either the 3.8-L bottles or the 19-L bottles (e.g., they were observed to tumble while ascending, probably after powered flight ended because the direction of motion was not observed to change substantially).

Safety considerations, precautions, and recommendations

Educational demonstrations that feature the combustion of alcohol must be done with great care. A great deal of heat can result. Alcohol flames can be nearly invisible in bright light, especially ethanol and methanol. Any supply bottle should be removed from the combustion site and tightly capped before initiating ignition. Any substantial pooling of fuel (as a liquid or a dense vapor) must be avoided. DO NOT POUR LIQUID FUEL NOR ATTEMPT TO INSTALL A NEW DEMONSTRATION BOTTLE UNTIL INSURING THAT NO FLAME REMAINS FROM A PREVIOUS DEMONSTRATION (feeling cautiously with a bare hand if necessary).

Only thin plastic bottles (not glass) should be used for whoosh demonstrations. High-velocity glass fragments created by the rupture of a glass bottle would be very hazardous without proper shielding.

All people should be well away from any region where a whoosh rocket might go during powered flight. It is also important to insure that everyone present is cognizant of each and every impending whoosh demonstration.

I advise that all whoosh demonstrations (bottle or rocket) be done with the expectation that it is possible for the plastic bottle to rupture when using any of these fuels. I advise that spectators should be at least 10 m from the combustion site.

At this distance, my experience indicates that ear protection is not required, even if a thin plastic bottle does rupture; and protective glasses are not required, if it is certain that spectators are clear of the potential flight path of a bottle. The demonstrator needs to be closer, and therefore should always use both eye and ear protection. Spark ignition is advised for all whoosh demonstrations because it allows the demonstrator to be at least 3 m from the combustion site.

My recommendation is that these demonstrations be presented to students by a professional adult demonstrator and that these fuels not be handled by students, especially young students. If older students do so, I recommend that they be vigilantly supervised.

All of the fuels discussed above are potentially hazardous to human health, although low concentrations can be safely metabolized. Oral ingestion should be avoided as well as any substantial inhalation of vapors or any substantial absorption of liquid through the skin. They can irritate skin and eyes upon contact. Careful fueling as specified above for occasional demonstration is expected to limit exposure to safe levels. Skin contact can normally be avoided completely even without the use of gloves (although use of gloves is a sensible precaution). Any of these liquids accidentally contacting the skin should be promptly wiped away or washed away with water, in which event it is not expected that a hazardous amount will be absorbed through the skin.

The United States Occupational Safety & Health Administration TLV-TWA (threshold limit value for a time weighted average) concentrations in air for continuous occupational exposures[17] are 200 ppm (parts per million) for both isopropanol and methanol. For ethanol, this limit is 1000 ppm (the toxicity of the chemicals used to denature laboratory ethanol should also be considered, typically 1% methanol and 4% isopropanol). For diethyl ether, this limit is 400 ppm. Also note that diethyl ether can form peroxides upon exposure to light and/or air, which are contact explosives when dry (commercial diethyl ether is typically supplied with trace amounts of BHT to reduce the formation of peroxides).

One should also mitigate the potential hazard due to the toxicity of combustion products from whoosh demonstrations. Gregory et al.[18] report that polycyclic aromatic hydrocarbons and other complex organic compounds are created by the whoosh bottle demonstration using isopropanol.

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