THE POTATO CANNON

Determination of Combustion Principles for Engineering Freshmen

HAZEL M. PIERSON, DOUGLAS M. PRICE
Youngstown State University • Youngstown, OH 44555

First-semester engineering students bring with them a spectrum of understanding of the engineering profession. They know that engineers design things, and they have been told you need to be good at math and science to be an engineer. While some are very committed to obtaining an engineering degree, others are not too sure if engineering is for them.

Engineering freshmen have taken courses in math and science in high school and generally obtained good grades, but they find their understanding of these subjects is limited as they try to apply their knowledge to real problems. The same is true of computing. They can manipulate the computer well, but when they are asked to apply computing solutions to real problems, they find their ability is limited.

In addition, many of these students are not prepared to interact in teams and to get along socially with other students. They come from many different high schools from all over the country, and they may be the only student coming to our college from their high school. In many instances they do not know anyone on their first day at class.

Engineering curriculums have basically ignored these problems in the past. Freshmen engineering students found they had a difficult schedule of math and science courses along with all the social adjustments required in the transition between high school and college. Without a strong commitment to obtaining an engineering degree, many capable engineering students would change majors or leave school prior to the sophomore year. Also, often those sophomores who did survive the engineering freshman year did not have the necessary background and commitment for the rigorous sophomore-level engineering courses. At Youngstown State University, as is the case at many engineering schools, a freshman engineering program was developed and instituted with the goal of improving retention of freshman engineering students, better preparing them for the remainder of the engineering curriculum, and giving them a taste of engineering in their freshman year.

GENERAL COURSE INFORMATION

A potato cannon project is part of the first-semester freshman engineering course at Youngstown State University. The design-based three-semester-hour course comprises two lecture hours and three laboratory hours per week. The lecture portion of the "Introduction to Engineering" course is conducted in a design/analysis-based lecture format in which the currently assigned project is used as a springboard for the lecture topics. There are typically three or four out-of-class design/analysis projects that span the semester. A brief introduction is given on the entire design process, broken into six steps:

1) *Problem Identification*
2) *Preliminary Ideas*
3) *Refinement*
4) *Analysis*
5) *Decision*
6) *Implementation*

This is done with the intention of making the students aware there is a methodical approach to design and problem solving that does not rule out creativity. This format allows for all aspects of any project they will encounter as an engineer to be addressed, from the first brainstorming session, to a prototype machine, to the final technical design report.

***Hazel M. Pierson** is currently Instructor of Mechanical Engineering and Freshman Engineering at Youngstown State University. Concurrently, she is finishing dissertation requirements for her PhD at the University of Akron. She received her BS in mechanical engineering at the University of Texas at Austin in 1985 and her MA in mechanical egineering at Youngstown State University in 1998. Her research interests are in the areas of vibrations, rotor dynamics, and advancd stress analysis.*
***Douglas M. Price** is Assistant Professor of Chemical Engineering and Chemical Engineering Program Coordinator at Youngstown State University. He received his BS from Pennsylvania State University in 1984 and his MA and PhD from the University of Notre Dame in 1986 and 1988, all in chemical engineering. His research interests are in the areas of heterogeneous reaction optimization, biofuels, and biomaterials.*

While discussing the design process, the majority of time is spent explaining the importance and application of the analysis step. The goal is to show how engineers use mathematical formulas to predict and evaluate design performance. Through the process, the students discover firsthand how the application of math and science principals fits into engineering design and analysis as well as how to systematically complete design and analysis at a level befitting an engineer.

The projects are a group venture with teams consisting of four members each. The students are allowed to form their own teams, and the vast majority of teams consist at least partially of members who have had no prior interaction with each other. To facilitate team formation and project execution, class time is taken to discuss team dynamics using the Tuckman Model.[1]

PROJECT INFORMATION

■ *Overview*

Projects for the semester are chosen in such a way as to present components from as many engineering disciplines as possible. Historically, chemical engineering has been poorly represented in the projects. In the fall of 2003, we decided to reverse this trend—and thus, the potato cannon project was born. Through this project, freshman engineering students are given an opportunity to integrate the principles of combustion chemistry and the physics of projectile motion.

Homemade potato cannons have been in use for many years, but with the Internet making it easy to share design ideas, they are once again arousing the curiosity of young inventors. The potato cannon provides an ideal way to introduce engineering principles to freshman students.

At the beginning of the project, the students are required to conduct a Web search on potato cannon technology, with an emphasis on the scientific principles inherent in this type of machine. This gives them a foundation for the project as well as building upon the Web-search instruction that they have received in their lab classes. Ultimately, the project requires that the students determine the kinetic energy of a potato fired from a cannon that is fueled by propane and air, and to compare this energy to theoretical predictions based on combustion chemistry.

The project begins with a brief introduction in class using a standard project assignment sheet. The students are informed of the project's guidelines, of the grading parameters, and of the project timetable. The Chemical Engineering Program Coordinator then explains the ultimate goal of the project—comparing the kinetic energy of the potato as it leaves the cannon with the theoretical amount of energy available from combustion. The principles of combustion chemistry, as they pertain to propane and methane, are presented and explained.

■ *Explanation of Combustion Chemistry*

The combustion of propane in air is given by

$$C_3H_8 + 5\,O_2 \rightarrow 3\,CO_2 + 4\,H_2O \tag{1}$$

The lower and upper flammability limits of propane in air at 25 °C are 2.2 and 9.5% by volume, respectively.[2] This gives the range of concentration of propane where an explosion can occur at atmospheric pressure and 25 °C. At the temperatures and pressures tested (10 to 25 °C and 1 atm), the ideal gas law is applicable and the energy released during the combustion of propane as a function of volume percent of propane within the range of the flammability limits can be calculated. To do this, it is necessary to determine which component, propane or oxygen, is the limiting reagent. Let x_{Propane} be the mole fraction of propane in air when it is in stoichiometric proportion to oxygen. The mole fraction of oxygen present can now be calculated as

$$x_{\text{Oxygen}} = 0.21\left(1 - x_{\text{Propane}}\right) \tag{2}$$

The ratio of the mole fraction of oxygen to that of propane must be equal to the ratio of their respective stoichiometric coefficients in the balanced chemical equation if they are to be in stoichiometric proportion.

$$\frac{x_{\text{Oxygen}}}{x_{\text{Propane}}} = \frac{0.21\left(1 - x_{\text{Propane}}\right)}{x_{\text{Propane}}} = 5 \tag{3}$$

Solving Eq. (3), the mole fraction of propane is 0.0403 when it is in stoichiometric proportion with oxygen. Assigning an energy release value of zero below and above the lower and upper flammability limits, respectively, the energy of combustion can be normalized on a unit volume of the fuel/air mixture basis as shown in

$$\begin{array}{ll}
\textit{Mole Fraction Propane} & \textit{Energy Release, } \hat{E}_c\textit{, kJ/liter} \\
x_{\text{Propane}} < 0.022 & = 0 \\
0.022 < x_{\text{Propane}} < 0.0403 & = \left(\dfrac{x_{\text{Propane}}}{22.4\dfrac{\text{liter}}{\text{gmole}}}\right) 2220\dfrac{\text{kJ}}{\text{gmole}} \\
0.0403 < x_{\text{Propane}} < 0.095 & = \dfrac{1}{5}\left(\dfrac{0.21\left(1 - x_{\text{Propane}}\right)}{22.4\dfrac{\text{liter}}{\text{gmole}}}\right) 2220\dfrac{\text{kJ}}{\text{gmole}} \\
> 0.095 & = 0
\end{array} \tag{4}$$

■ *Potato Cannon Design*

The potato cannon project does not include a student design component of the cannon itself, for safety and liability reasons. For the actual in-class study and analysis, three cannons of varying combustion-chamber dimensions were used. Aside from the different combustion-chamber sizes, the three cannons were identical. All plastic components were made from Schedule 80 PVC pipe and fittings. A materials list for the cannons is presented in Table 1 and a schematic of the 3-inch-diameter by 12-inch-length combustion chamber cannon is shown in Figure 1.

■ *Explanation of the Kinetic Energy of the Potato*

The kinetic energy, E_k, of the potato leaving the barrel of the cannon is given by

$$E_k = \frac{mdg}{4\sin\theta\cos\theta} \qquad (5)$$

where m is the mass of the potato, d is the horizontal distance the potato traveled, g is the gravitational acceleration and θ is the angle of the barrel with respect to horizontal.

Dividing the kinetic energy by the volume of the combustion chamber to give a normalized energy gives

$$\hat{E}_k = \frac{4\,E_k}{\pi D^2 L} \qquad (6)$$

where D is the diameter of the combustion chamber and L is its length. The final equations of the derivation provide a means to determine the kinetic energy in terms of easily measurable variables: the mass of the potato, the angle of the cannon, the horizontal distance of potato travel, and the geometric size of the cannon barrel.

■ *Field Experiment*

As was stated earlier, three cannons of varying combustion chamber sizes were considered and analyzed in this project. Figure 2 shows the completed cannons. For the experiment, propane gas was quantitatively added via a calibrated syringe to the combustion chamber which was previously filled with air at ambient conditions. Potatoes of known mass were fired from the cannon at three different elevation angles and the linear distance traveled was recorded. To meter in a specific amount of propane fuel, the students extracted propane from the tank using a syringe (see Figure 3) and injected the propane into the combustion chamber.

The cannon was placed in a wooden cradle made of 3/4" plywood. The cannons were fired at angles of 30-, 45-, and 60° from the ground. Figure 4 shows the cannon just prior to cannon fire. Notice the distance of the student from the cannon. This again was designed for safety purposes. The pulled string was attached to a cantilevered thin sheet of metal. When pulled, the metal actuated the piezoelectric igniter.

TABLE 1
Material Supply List for Potato Cannons

Cannon	*Small*	*Medium*	*Large*
Barrel	2" diameter by 24"		
Combustion Chamber	3" diameter by 6" 3" PVC end cap 3" to 2" reducer	3" diameter by 12" 3" PVC end cap 3" to 2" reducer	4" diameter by 12" 4" PVC end cap 4" to 3" reducer 3" to 2" bushing
General	ball valves, piezo igniters, pins, PVC cement		

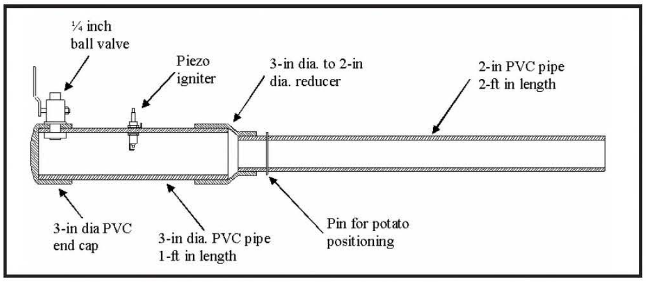

Figure 1. *Schematic of potato cannon design.*

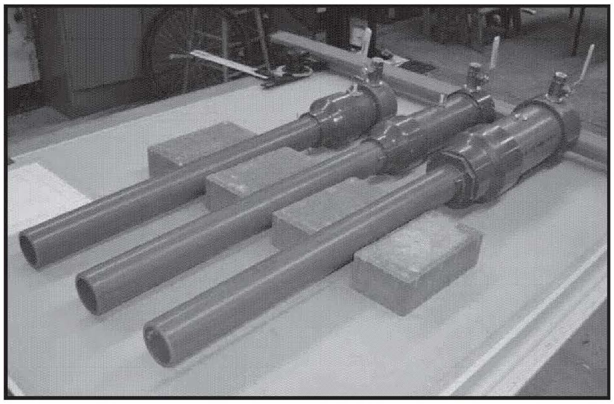

Figure 2. *Three cannons used in the project.*

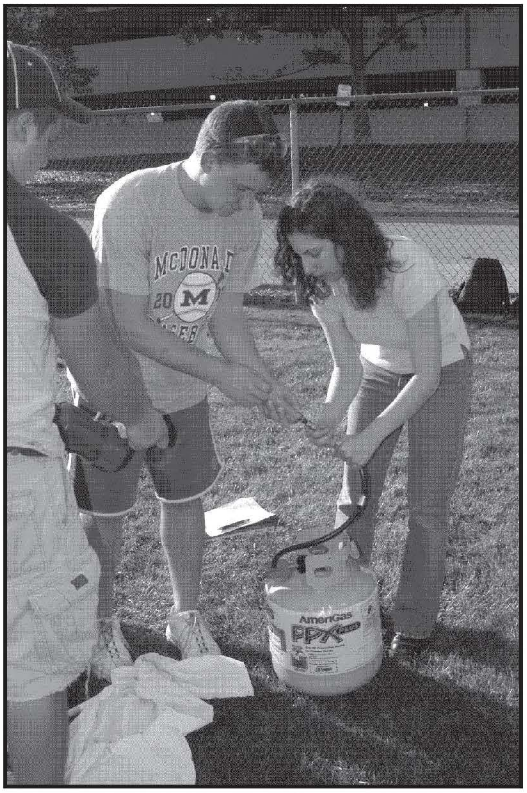

Figure 3. *Extracting fuel from a propane tank.*

Once the potato fired, the distance of horizontal travel was measured using a Bushnell Yardage Pro Compact 600 Laser Range Finder.

■ ***Results***

The students were required to use the collected data taken over a period of four days to calculate the kinetic energy of the potatoes utilizing the mass, the distance, and the angle. This kinetic energy was normalized to the volume of the combustion chamber and then compared to the volume percentage of propane in the combustion chamber prior to firing. Figure 5 shows the results of the firings of the three potato cannons along with the theoretical energy release based on the combustion energy.

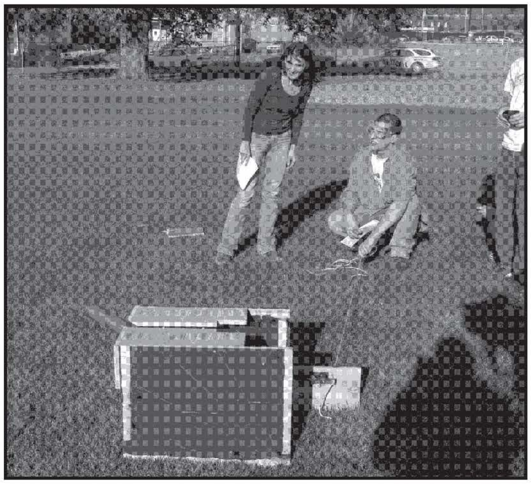

Figure 4. *Firing the cannon.*

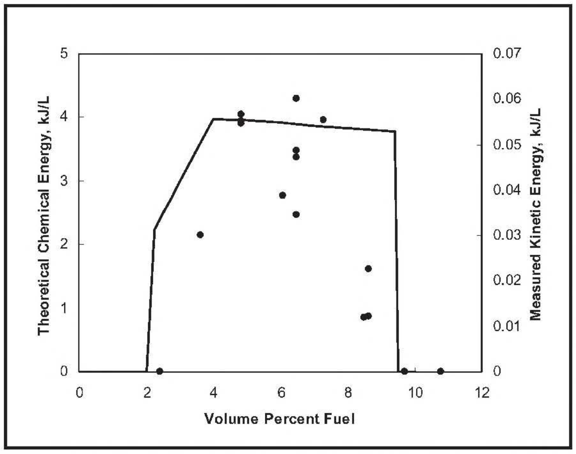

Figure 5. *Energy generated during the combustion of propane.*

Academic Year	ENGR 1550 Enrollment	Enrolled in Engineering Following Year	Percent of Retained Engineering Students Entering ChE Program
2001-2002	152	110	6.4%
2002-2003	139	88	9.1%
2003-2004	140	101	12.9%

TABLE 2
Recruitment of Students into ChE Program

During explosive combustion, approximately 1% to 10% of the available chemical energy is actually transferred into mechanical energy.[3] Figure 5 shows the experimentally determined combustible range for propane is approximately 2.5% to 9.8%. This is in good agreement with the literature values. Figure 5 also shows that the kinetic energy based on the experimentally measured firing distance is approximately 0.5% to 1.5% of the calculated chemical energy potential. This also is in good agreement with literature values.

CONCLUSIONS

Table 2 shows the data on retention of engineering students from the freshmen to the sophomore year and the percentage of retained students entering the chemical engineering program. Although further data collection is necessary to draw statistically significant conclusions, the percentage of engineering students selecting chemical engineering as their major showed a marked increase after the potato cannon project was initiated.

The potato cannon project was a positive growth experience for the freshmen engineering students. It provided the students an opportunity to use physical world knowledge that they already possessed, such as projectile motion. On the other hand, it challenged the student by requiring them to now scientifically identify and properly model these physical world occurrences. They used math, science, and computing skills to solve a problem much like many "real" engineering problems. It also gave a practical application to the computer skills they were simultaneously learning in their lab classes. In addition to this, the students learn the pros and cons of teamwork, they develop lasting friendships, and they have a lot of fun while testing and analyzing the cannons. Students worked in the engineering laboratories and worked to collect data accurately.

The students evaluated the course in a written class survey at the end of the semester. They were asked their opinion concerning how well each activity added to their understanding of the field of engineering. Of the four design projects conducted throughout the semester, the potato cannon project received the most all-around favorable remarks. One of the most common remarks was the students' amazement that the mathematical modeling of the combustion actually correlated to the experiment. Finally, they were required to write an engineering report documenting their work and formulating conclusions from their results. This gave the students a good introduction into what engineering is all about and what types of work engineers do.

REFERENCES

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3. Crowl, D.A., and J.F. Louvar, *Chemical Process Safety: Fundamentals with Applications*, 2nd ed, Prentice Hall (2002) ❐