6-2017

Cannons to Spark Thermal-Fluid Canons

Francis M. Haas
Rowan University, haas@rowan.edu

Nicholas W. Dow

Thomas L. Merrill
Rowan University, merrill@rowan.edu

Smitesh Bakrania
Rowan University, bakrania@rowan.edu

Recommended Citation

Haas, F. M., Dow, N. W., Merrill, T., & Bakrania, S. (2017, June), *Cannons to Spark Thermal-Fluid Canons* Paper presented at 2017 ASEE Annual Conference & Exposition, Columbus, Ohio. https://peer.asee.org/28007.

Paper ID #19046

Cannons to Spark Thermal-Fluid Canons

Dr. Francis (Mac) Haas, Rowan University

Mac Haas is an Assistant Professor of Mechanical Engineering at Rowan University. His primary research interests include chemically reacting flows applied to energy conversion and air pollutant formation/destruction.

Mr. Nicholas William Dow
Dr. Tom Merrill, Rowan University

Dr. Tom Merrill's research interests include energy systems, biotransport modeling, and medical devices. Prior to Rowan University, Dr. Merrill worked for thirteen years at a number of places including United Technologies Carrier, Abiomed, Wyeth Research, MicroDose Technologies, and at a medical device start-up company called FocalCool. He received his degrees in Mechanical Engineering from Penn State (Ph.D.), the University of Michigan (M.S.), and Bucknell University (B.S.). He currently teaches thermodynamics, heat transfer, fluid mechanics, and biofluids.

Dr. Smitesh Bakrania, Rowan University

Dr. Smitesh Bakrania is an associate professor in Mechanical Engineering at Rowan University. He received his Ph.D. from University of Michigan in 2008 and his B.S. from Union College in 2003. His research interests include combustion synthesis of nanoparticles and combustion catalysis using nanoparticles. He is also involved in developing educational apps for instructional and research purposes.

Cannons to spark thermal-fluid canons

Abstract

Hands-on projects are launch pads for sparking student interest. Specifically, design-build-test (DBT) projects can be effective tools for boosting students' confidence in their ability to apply theoretical knowledge to practical engineering. Recognizing the need for relating the theoretical aspects of thermodynamics to its application, an air cannon design-build-test project was envisioned and implemented.

Air cannons can be simple and inexpensive to construct, while offering a robust platform to explore thermodynamics, heat transfer, and fluid mechanics concepts. At the same time, the ability to launch projectiles from the cannons carries an obvious appeal for many students. An air cannon design project was integrated towards the beginning of a year-long thermal-fluid sciences course series. The primary aim of the project was for student teams to study how air cannons function and subsequently design a prototype that fits "customer" specifications. Each team constructed their cannons using PVC piping to launch acetal plastic projectiles. Students were additionally required to design a functional release valve mechanism to trigger the projectile launch. To aid in evaluation of their designs, students were introduced to a numerical-analytical modeling approach to explain air cannon behavior using principles of linear momentum conservation and ideal gas thermodynamics theory. Among other metrics, the performance of each student team was assessed based on (1) the ability of the custom trigger mechanism to fire the cannon over a range of initial reservoir pressures, (2) a thoughtful comparison among experimentally-measured and model-predicted muzzle velocities, and (3) documentation of the results of cannon design, realization, and operation.

This paper discusses the implementation and relevant outcomes of the project. Based on student feedback, the project was well-received and anchored the often abstract thermal-fluid sciences concepts taught. The project also highlighted the challenges of applying theoretical equations to real-world problems and the vital need for experiments to improve accuracy of theoretical models. Exposure to this iterative approach to design emphasizes the practical aspects of engineering challenges. Overall, the project served its primary purpose of engaging students with thermodynamics concepts. With minor modifications in implementation, the project can appeal to students with a broader academic focus and experience.

Introduction

Traditional lecture and textbook delivery of many fundamental engineering subjects serves to introduce elementary analytical approaches distilled from the complexities of the "real world." However, such distillation often precludes conveying and contextualizing the nuance and interrelatedness of "real-world" engineering applications. An additional criticism of the traditional approach is that it lacks a certain "WOW" factor[1] that sparks student interest and entices engagement and active learning. Accordingly, a significant body of literature related to hands-on, design-build-test (DBT) projects has grown to address the gaps in student engagement and between classroom theory and practical implementation.[2-6] The relative merits and demerits of DBT-type projects over pre-designed laboratory experiments are discussed elsewhere;[2,3]

nevertheless, in parsing the design ambiguities associated with open-ended DBT projects, students certainly employ some non-technical competencies such as imagination and resourcefulness. These skills are desirable in engineering graduates, but are typically not exercised in pre-designed laboratory experiments despite similar intention for reinforcing classroom theory.

In the present paper, we describe a project involving the design, construction, testing, and analysis of a pneumatic (air) cannon. The project was conceived as a five week-long module of the 2-credit integrated Thermal-Fluid Sciences[a] Practicum course at Rowan University, typically taken by first-semester third-year mechanical engineering (ME) students in conjunction with a 4-credit Thermal-Fluid Sciences lecture. In recent years, the Practicum course time devoted to this module has focused instead on development of an air-powered engine that acts as the mechanical power plant for a hybrid powertrain system to be developed over five semesters of the ME curriculum.[4] However, due to increasing pressure on fixed laboratory space and project resources (e.g., large machines, qualified machine shop assistance) resulting from increased enrollment, concurrent air engine development by multiple sections of the Practicum course could no longer be accommodated.[b] From a "design the design project" perspective, our mandate was to develop a meaningful substitute project that

(1) aligned with certain topics concurrently covered in the theory/lecture portion of the Thermal-Fluid Sciences course,
(2) integrated concepts from other sub-disciplines of the mechanical engineering curriculum,
(3) challenged students with open-ended design ambiguity and the need to make choices,[7]
(4) could be implemented on a relatively limited space, time and financial budget, and
(5) provided a "WOW" factor[1] to boost student engagement.

This project brings together and reinforces several concepts of thermal-fluid sciences, such as expansion of (an ideal) gas, compressible flow, transient flow, flow across a valve, gauge and absolute pressure, hydrostatic equilibrium, etc. However, our particular implementation of the project requires students to invoke concepts and skills from a broad base of their technical coursework up to and including their third year, including dynamics, thermodynamics, fluid mechanics, introductory circuits, numerical methods and ordinary differential equations, manufacturing, data acquisition and reduction components of prior lab courses, and introductory computer science. In this sense, the cross-disciplinary nature of our implementation

(1) differentiates it from other implementations of cannon-type projects previously described elsewhere, including in *these* conference proceedings,[1,7-15] and
(2) indicates its adaptability for courses that do not focus on thermal-fluid sciences *per se*.

---

[a] Herein "thermal-fluid sciences" includes the subjects of engineering thermodynamics, fluid mechanics, and heat transfer.

[b] Construction of air engines for these sections was deferred until the following semester.

Background

An air cannon (Figure 1) is essentially composed of a valve separating a reservoir of volume V_0 containing high pressure air at initial charge pressure and temperature of P_0 and T_0 from a barrel of length L and diameter d containing a projectile of mass m that may be displaced relative to the valve by some small distance L_0. The ratio of specific heats for air is γ and is assumed to be constant.

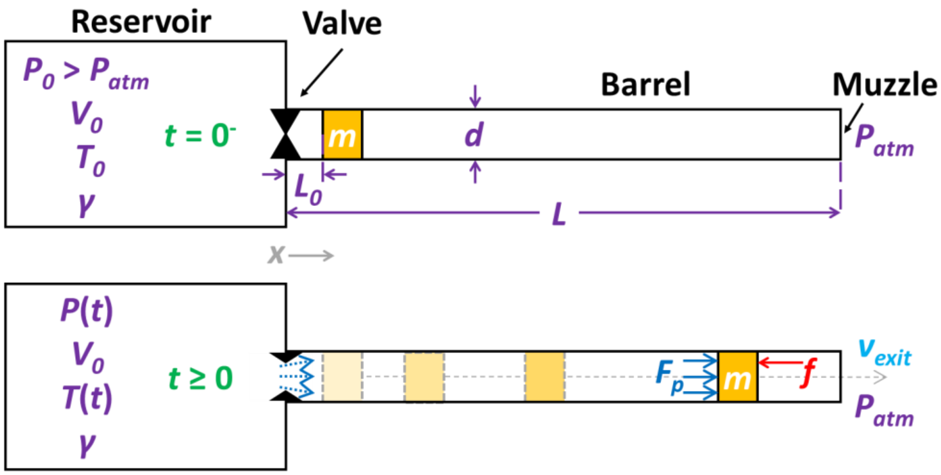

Figure 1. Air cannon schematic indicating key geometric, dynamic, and thermodynamic parameters before (top) and after (bottom) valve opening.

Upon valve opening at $t = 0$, the high pressure air acting on the reservoir side of the projectile generates a force F_p on the projectile. Provided this force is sufficient to overcome friction f between the barrel and projectile, and neglecting gravity, the force due to pressure drives the projectile along the barrel towards the muzzle. After the projectile completely exits the barrel, the net pressure force on it drops to zero and it continues to move subject to its final muzzle velocity, v_{exit}, and gravitational effects. In the present implementation, we did not pursue the dynamics of ballistics or air resistance.

The equations of motion for the projectile can be derived subject to certain assumptions regarding the expansion of the high pressure air over the valve.[8] Solution of these equations permits determination of projectile dynamics. In the present cannon implementation, we focused on the muzzle velocity, v_{exit}, which can be determined from system parameters by, for example,

$$v_{exit,iso} = \sqrt{\frac{2}{m}\left(P_0 V_0 ln\left(1 + \frac{\pi d^2 L}{4V_0}\right) - \frac{\pi d^2}{4} L P_{atm} - Lf\right)} \tag{1}$$

in the case of assumption of a quasi-static isothermal expansion with no initial projectile displacement L_0 and no flowrate limitations imposed by the valve (i.e., unobstructed flow). Here the additional "iso" subscript on v_{exit} indicates isothermal expansion, and absolute rather than gauge pressures are invoked. Other model variants are discussed later.

Considering the complex functional dependence of even a single observable (i.e., v_{exit}) on the broad parameter space implied by the preceding description and results of Equation 1, student groups were not tasked with *de novo* construction of air cannons. Instead, each group of five students was asked to use four weeks to develop three key components of an extended air cannon system subject to constraints provided to them in the initial design challenge: (A) a fast-acting pressure release valve, (B) a muzzle velocity measurement circuit, and (C) a velocity-corroborating, energy-absorbing projectile backstop. As borne out by generally successful completion of (A)-(C) and sub-system integration (functional air cannons developed by 13 of 14 teams by test day), this set of deliverables was of appropriate scope for the allotted project time and group size.

Summary of Deliverables

By the beginning of Project Week 5 (see timeline in Figure 2), student design groups were tasked with

- developing three key components of an air cannon system and integrating them into a functional cannon design (design & build)
- developing three parametric models for muzzle velocity vs. reservoir charge pressure (design & build)
- using their air cannon assemblies to develop muzzle velocity vs. reservoir charge pressure measurements (testing)

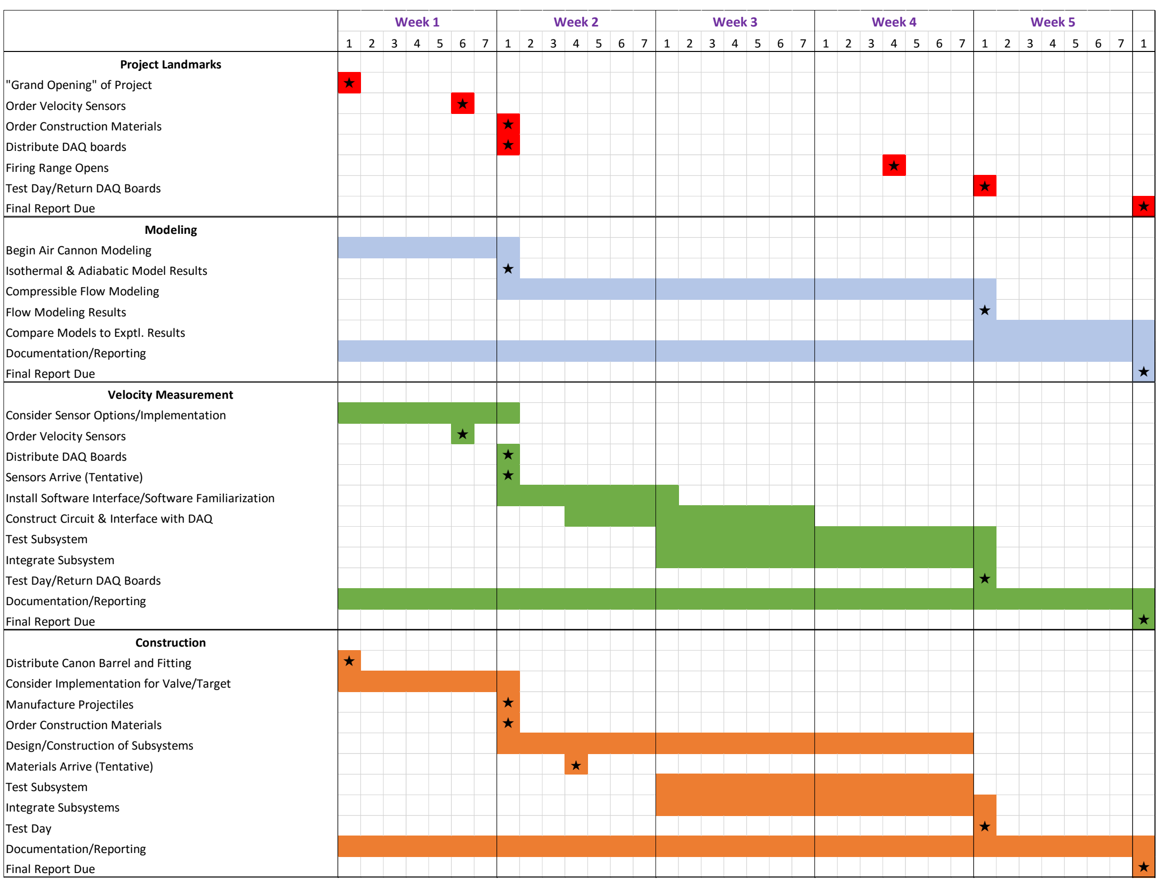

Figure 2. "Recommended" project timeline similar to the one presented to students.

Project Week 5 was devoted to solidifying parametric inputs for the air cannon models, using them to simulate muzzle velocities, and comparing among simulated and experimental results. These were documented in a final report detailing both the physical subsystem design and comparison of its performance to the theory-based models.

Essential background for further understanding these deliverables in context is presented in the following sections.

Project Implementation

Timeline

Figure 2 shows a timeline for the project similar to the one provided to student design teams upon introduction of the project. Aside from specific landmark dates for ordering materials and testing cannons, the provided timeline was offered only as recommendation. Each student group was left to develop its own particular timeline and division of labor for delivering a functioning air cannon and final report by the specified due dates. Nevertheless, students positively cited provision of this recommended timeline several times in the project feedback. The entire project can be reasonably contained in ~5 weeks of class time, depending on final reporting requirements.

<u>Week 1</u>

In our implementation, Week 1 primarily involved broadly introducing the project, parts and materials distribution, defining "customer-provided" facilities such as a cannon firing range and air pressure reservoirs, stimulating ideas related to key subsystems to-be-designed, and setting timelines for additional parts and raw material ordering.

Limited lecture time (<1 hr), primarily intended to stimulate the brainstorming process, was devoted to discussing the need for a valve of "fast-acting" nature (i.e., the need for well-posed initial conditions for derivation of Equation 1 and other modeling discussed later) and some design concepts for achieving this (e.g., a rupture diaphragm, solenoid valve, and a "Supah-style" valve[9]). Three instructor-provided choices for inexpensive (< $5) muzzle velocity sensors, including a mechanical limit switch and two forms of infrared optical sensors were also briefly presented. However, the initial statement of design challenge for the velocity-corroborating, energy-absorbing backstop was left completely open-ended.

Theory (e.g., Equation 1) for unobstructed isothermal modeling of projectile dynamics was also developed to facilitate initial attempts at air cannon modeling. Despite the simplifying assumptions of this model, it provides some insight on the role of many cannon design parameters, as well as a leaping-off point for development of alternative models.

<u>Weeks 2 & 3</u>

In emulation of a design-and-deliver process with significant "customer" involvement, teams were able to solicit design feedback during meetings with the instructor in both Week 2 and Week 3 of the project, which also provided an opportunity for groups to clarify any lingering questions about the design objectives, communally-available facilities, etc.

In Week 2, each team met with the instructor for ~30 minutes to discuss design ideas and gain access to a $50 "flexible spending account" to order additional materials previously identified as necessary for air cannon component construction. This account could be spent at one of two general-purpose vendors of tools, hardware, and raw materials. Any unused funds were forfeited after the class order was placed early in Week 2 of the project. Prior to the Week 2 meetings, a brief lecture was also presented to develop theory necessary for compressible (obstructed) flow modeling of the air cannon, further discussed below.

The formal ~30 minute instructor feedback meetings with each team were repeated in Week 3, though the bulk of class time was devoted to free work on the project.

Week 4
Groups pursued free design, construction, and testing according to their own modifications to the representative timeline of Figure 2.

Week 5
Air cannons were tested on Day 1 of Week 5. The balance of the week was spent on data analysis, comparison to modeling, reporting, etc. In our implementation, the final report was due on Day 1 of Week 6.

Additional Implementation Considerations for Physical Air Cannon Components
In Week 1, each team was provided with up to 3' of ¾" diameter Schedule 40 PVC pipe to be used as the barrel of the cannon, and between 1" and 2" of 7/8" diameter acetal rod to be used in the manufacture of a blunt projectile. Other construction materials for subsystem deliverables A-C (the pressure release valve, muzzle velocity circuit, and velocity-corroborating backstop, respectively) were either sourced from raw materials (wood, metal plate and rods, springs, gasket material, etc.) already available in-house at Rowan or ordered through the $50 flexible spending account.

As a project platform, it is easy to envision variants of this project that (de)emphasize or modify aspects of the present implementation. For instance, less complicated variations of the project may provide solenoid valves for (A) rather than seeking independent valve designs, or (C) could be dispensed with altogether provided some alternative for dealing with fast moving projectiles (some > 100 mph) is used.

Alternative implementations aside, under the present design challenge, each of components (A), (B), and (C) were then to be interfaced by the cannon test date (beginning of Week 5) into a single integrated system involving other instructor-provided, communally-available cannon components and testing facilities. These facilities included several high pressure (≤ 50 psig) reservoirs (comprised of relatively expensive charging valves, overpressure safety releases, and pressure gauges) as well as a safe firing range. These accommodations were provided partly to address costs, ensure a degree of uniformity and functional consistency, and mitigate safety concerns. As well, these "given" facilities permitted discussion of both standardization and customer requirements, which are topics that are less likely to come up in traditional theory-based lectures for engineering fundamentals.

Aside from the aforementioned PVC barrel and acetal rod, teams were offered several additional resources to aid in project completion. Existing university-owned National Instruments myDAQ data acquisition boards and/or personally-owned Arduino Uno boards were allowed as options for acquiring measurements from the velocity measurement circuits according to each team's preferences. Some groups also used these to log data from their backstops.

To assist groups with pre-deadline testing of their components, whether individually or as sub-system assemblies, several communal facilities were also made available in Weeks 3 and 4 of the project. One of the high pressure reservoirs was provided to assist in testing of fast-acting valve actuation and leak resistance. Another was deployed with an off-the-shelf solenoid (fast-acting valve) and barrel as a tool for independent verification of velocity measurement circuits and energy-absorbing backstops.

Considerations for Air Cannon Modeling

In addition to construction and integration of physical air cannon components, each group of five students was also asked to develop three models of the projectile dynamics for later comparison among each other and to experimentally-acquired projectile velocities determined at the muzzle and backstop. Two of these were closed-form parametric models for muzzle velocity v_{exit}, such as indicated by Equation 1 for an unobstructed, quasi-static isothermal gas expansion over the air cannon fast-acting valve, or

$$v_{exit,ad} = \sqrt{\frac{2}{m}\left(\frac{P_0 V_0}{\gamma-1}\left(1-\left(\frac{4V_0}{\pi d^2 L+4V_0}\right)^{\gamma-1}\right)-\frac{\pi d^2}{4}LP_{atm}-Lf\right)} \qquad (2)$$

for an unobstructed, quasi-static adiabatic gas expansion over the valve. Both of these models/equations were developed during lecture time to demonstrate commonality with an approach for treating the third, more complex case involving choked flow across the valve. Detailed development of these models, including the third, is presented by Rohrbach et al.[8] and is not repeated here, although relevant features are discussed below and were presented in Week 1 and Week 2 lectures.

Briefly, an imbalance among forces due to reservoir-side high pressure, atmosphere-side low pressure, and friction govern the one-dimensional dynamics of the projectile (Figure 1). Of these, the magnitude of the high pressure force is unsteady and depends on the reservoir depressurization process across the valve. The case of valve-obstructed flow requires explicit solution of a coupled material balance across the valve. This is unlike the quasi-static expansion models that parameterize $P(t)$ reduction in terms of thermodynamic expansions linked to high-pressure side increases in $V(t)$ as a linear function of projectile displacement x. Obstructed flow modeling also requires introduction of a new model parameter, $P_b(t)$ (not indicated in Figure 1), which is the pressure between the open valve and the projectile. Except in limiting cases, $P_b(t)$ will be neither the reservoir pressure, $P(t)$, nor atmospheric pressure, P_{atm}, and is related to both the displacement of the projectile as well as the total amount of air that has crossed the valve since opening.

Determination of P_b and its associated force effectively requires simultaneous solution of a fluid mechanics mass conservation law and a rigid body dynamics linear momentum law. Moreover, when the approximate inequality $P_b(t) \leq ½ P(t)$ (a result from compressible flow) is satisfied, flow across the valve will choke and the functional dependence of the air flow rate across the valve changes from one that depends on both P and P_b to one that depends only on P. The situation may seem daunting, particularly for students who have little experience with problems simultaneously employing several fundamental concepts (i.e., consequences of the ideal gas law, mass/mole conservation, conservation of linear momentum, and geometric insight). Fortunately, the relatively complicated, coupled ODEs and conditional source term dependencies of obstructed flow readily lend themselves to numerical solution.

Accordingly, relevant details of the obstructed flow model, including a manufacturer's recommended equations for choked and non-choked flow over valves,[16] were presented during lecture, as was theory and exercise using a simple forward Euler numerical integration scheme to be implemented using either a spreadsheet or Matlab. In the interest of informal assessment of student engagement with the modeling component of this project, extended open lecture discussion was intentionally suppressed regarding treatment of two key unknown model parameters, namely the frictional force and the effective fast-acting valve flow coefficient, C_v. Instead, approaches to determine these were discussed only with groups that initiated an inquiry. Notably, there is little likelihood that two or more of the custom-designed fast-acting valves developed for this project should have the same flow coefficient, so use of the same C_v value by different groups may indicate a lapse in critical thinking or initiative during the development and exercise of the obstructed flow model.

Results

Representative Student Products

Figures 3-5 demonstrate exemplar student-produced schematics and photographs for (A) fast-acting valves, (B) muzzle velocity sensor circuits and hardware supports, and (C) velocity-corroborating backstops. We attribute the diversity in valve and backstop designs to our intentional avoidance of prescribed designs, though some groups did follow through with provided lecture material, as evidenced in the Supah-style[9] valve implementation shown in Figure 3.

Despite three sensor options provided for the muzzle velocity measurement circuits, groups unanimously (14 groups of 14 total groups) chose infrared break-beam sensors as the defining elements of their myDAQ or Arduino Uno circuits, even despite prior use of the alternatively offered infrared reflectance sensor earlier in the Practicum course. Given that groups had many other opportunities for (limited) choice across the present project implementation, these results suggest that a multiplicity of options for this aspect of the design is likely unnecessary in future implementations of the project.

While there was convergence on the type of sensor used for muzzle velocity determination, subtle differences among student design implementations were evident. Figure 4 demonstrates two variations on design of the circuit and the hardware mounting it to the air cannon muzzle. These examples were selected to highlight design diversity evident in student-produced solutions: one sensor vs. two, Ardiuno (not shown) vs. myDAQ data acquisition, and laser-cut vs. 3-D printed mounting hardware.

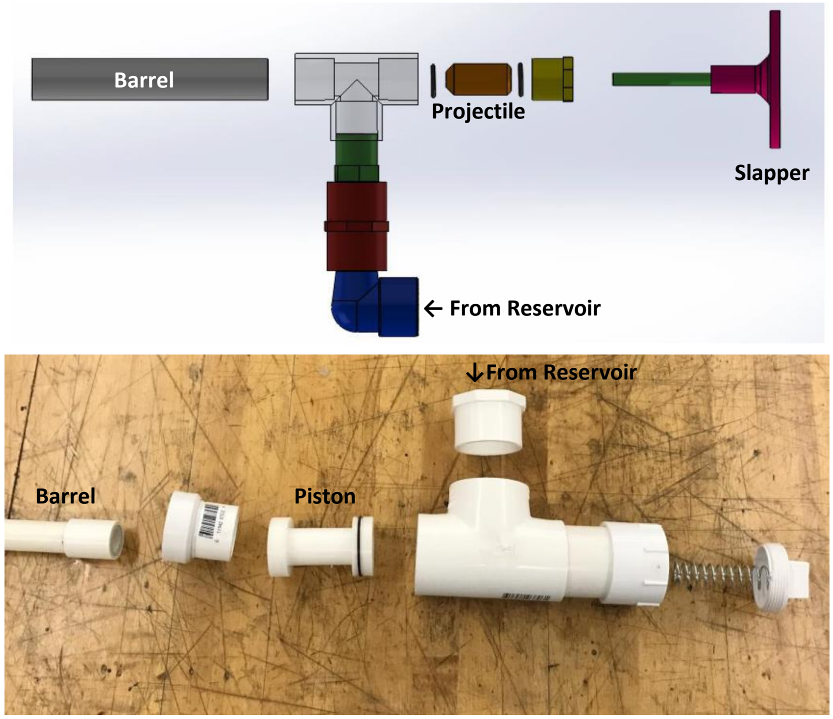

Figure 3. Examples of fast-acting valve designs: (top) a design using a slapped piston to disengage the projectile from O-rings anchored in the PVC tee – in this case, the projectile itself acts as part of the valve; (bottom) a design based on the Supah-style[9] valve.

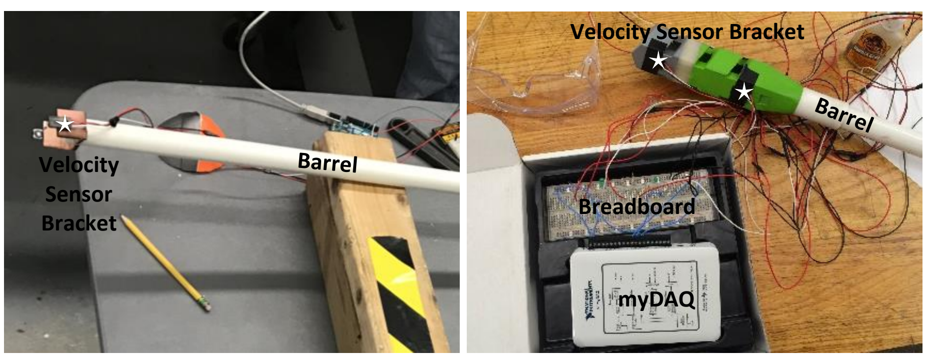

Figure 4. Examples of velocity measurement circuit designs, with muzzle mounting hardware: (left) a single sensor, Arduino-driven circuit supported by laser-cut mounting hardware; (right) a two-sensor, myDAQ-driven circuit supported by a 3-D printed mount. Break-beam sensors indicated by "★" in both images.

Among the air cannon component deliverables, the energy-absorbing, velocity-corroborating backstops demonstrated the greatest diversity in design. Backstops ranged from the ballistic pendulum and spring-loaded plunger concepts demonstrated in Figure 5 to padded carts and sliding blocks of foamed polystyrene. Despite several discussions during design feedback meetings, student groups broadly eschewed designs involving a second circuit for automatic logging of velocity-corroborating data (e.g., potentiometer-facilitated pendulum displacement angle measurement).

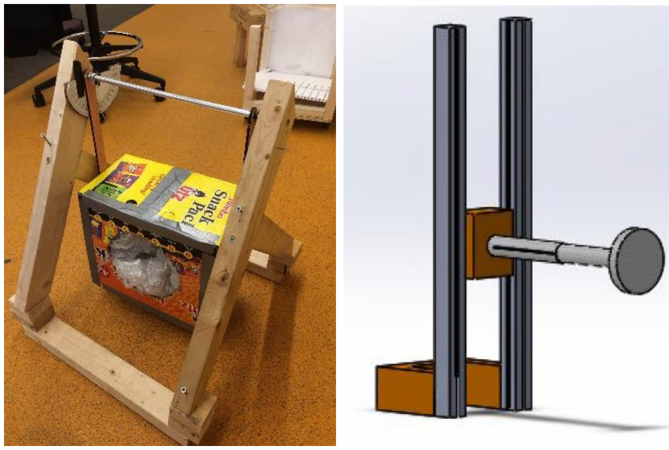

Figure 5. Examples of energy-absorbing, velocity-corroborating backstops: (left) a ballistic pendulum with manual angle indicator, (right) a spring-loaded plunger with compression indicator.

General correlation of backstop performance observables (e.g., pendulum displacement angle, plunger depression, etc.) with velocity was evident in each backstop design. However, proper treatment of the momentum and energy conservation principles underpinning most designs was broadly lacking, whether in treating inelastic collisions as elastic, disregarding projectile reflection off of uncushioned surfaces, or the like. This generally led to significant discrepancy between inferred projectile velocity at the backstop and directly measured velocity at the air cannon muzzle. This result suggests that future project implementations may benefit both from a limitation in scope for backstop design, as well as classroom review of the physics applicable to backstops of this more limited scope.

For sake of completeness, Figure 6 shows an air cannon assembly, up to and including the muzzle velocity measurement circuit. Representative backstops may be inferred from Figure 5. Herein evident are the 3/4” diameter Schedule 40 PVC pipe barrel provided to each group, as well as the communal high pressure reservoir with air charging and pressure control hardware.

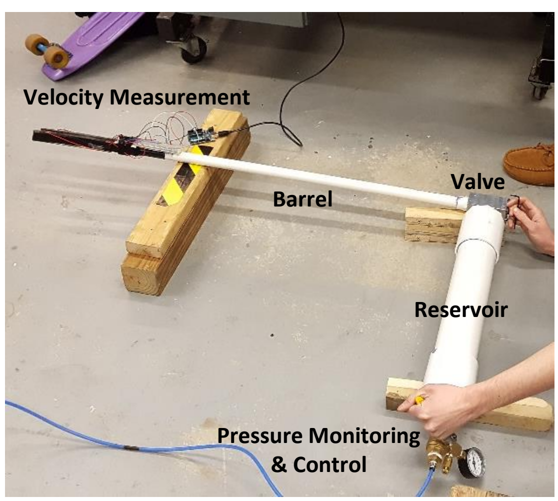

Figure 6. Example of a complete air cannon assembly.

The student-generated experimental and modeling results of Figure 7 condense the key deliverables of the present project implementation that would also likely appear following a pre-designed laboratory experiment. On a single set of axes

(1) direct experimental measurements of muzzle velocity vs. initial reservoir charge pressure can be compared to muzzle velocities inferred from experimentally measured backstop performance (points-to-points comparison),

(2) direct and inferred experimental muzzle velocities can be compared to predictions of each of the three models described earlier (points-to-lines comparison), and

(3) modeling results can be compared among each other (lines-to-lines comparison).

This set of exemplar results includes both consideration of an effective flow coefficient (C_v = 1.25) and an allowance for frictional effects (~3 psi). Both of these parameters are particular to individual air canon system design, and are not known or calculable *a priori*. Hence, the experimental data are vital in providing empirical constraint of flow coefficient and friction parameters in the theoretical models. This serves as a useful lesson regarding calibration of experiments and measuring devices.

However, not all groups generated a plot similar to the one shown in Figure 7. For example, several showed straight lines of best fit passing through measured v_{exit} vs. P_0 data along with model-predicted lines plotted separately, indicating a general lack of consideration for the underlying physics or the purpose of the modeling. Unsurprisingly, these results generally excluded experimentally-informed treatment of flow coefficient and/or friction.

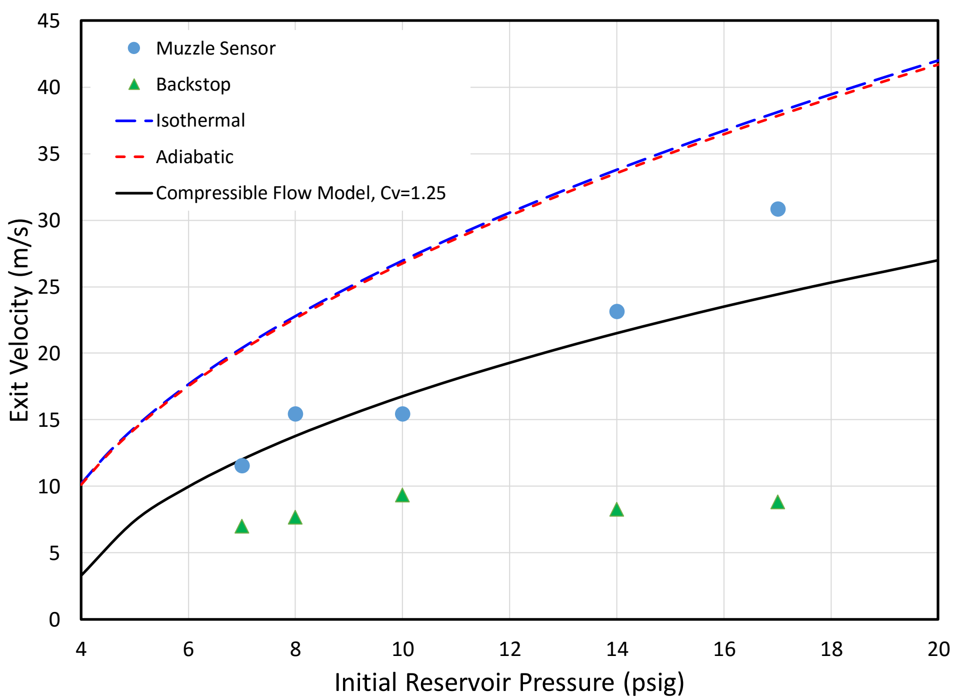

Figure 7. Student-generated comparison of modeling results, directly measured (sensor) muzzle velocities, and backstop-inferred velocities.

Feedback and Assessment
Student feedback regarding the project was broadly positive, in accord with other implementations of cannon-related projects and suggesting the "WOW" factor was achieved. Rather than completing a Likert-type survey, students wrote verbose technical memoranda discussing positive and negative points of the project, in alignment with technical writing objectives of the Practicum course. This admittedly makes quantitative assessment of the project difficult; however, we believe that the degree of personal investment for memo writing provides a kind of insight unavailable to even the best-designed Likert-type surveys. We present below some representative, paraphrased "pros and cons" for the present project implementation, as gleaned from student memos:

Positives
- Fun Project
- Recommended project timeline helped with time management
- Backstop idea was a novel twist and stimulates open-ended thinking
- Design feedback meetings with instructor were constructive
- Disappointment when final design did not initially work indicates emotional investment in project/outcome

Negatives
- Obstructed (compressible) flow modeling was too hard; many students claimed to lack appropriate coding background
- Velocity measurement circuit not relevant to thermal-fluid sciences
- Communal resources suffered wear and tear (e.g., worn out sealing threads, broken pressure gauge)

Instructor Reflections and Recommendations for Future Implementations
This implementation of an air cannon project satisfied our program needs to address resource pressures due to growing enrollment – likely also a persistent and widespread issue in other programs – while embracing a multidisciplinary approach to teaching key concepts of thermal-fluid sciences. The platform basis of the project permits scalability to accommodate different group sizes and background proficiencies, and the platform is versatile enough that it can be used even independently of a thermal-fluid sciences focus.

Development of communal facilities like high pressure reservoirs; independent test facilities for valves, velocity measurement circuits, and backstops; and firing ranges significantly reduced per-team costs by limiting the need to replicate relatively expensive flow/pressure control components across all 14 of our groups. The inherent standardization of these facilities also ensured a degree of safe operation that could not be assured with student-designed apparatus. Project costs were primarily absorbed by available in-house inventory and the $50/team allowance, though on average, this was utilized at a rate closer to $25/team.

As a design-build-test (DBT) -type project, our implementation interweaves elements of the mechanical engineering canon including rapid prototyping, engineering mathematics, coding, dynamics, etc. into a creative design opportunity that was well-received by our students. Despite the general success of our inaugural implementation of this project, many opportunities for improvement remain for future project iterations, including

- enhanced support of code development for compressible flow modeling,
- emphasis *to students* that no one sub-discipline of engineering stands alone, and hence "velocity measurement circuits *are* relevant to thermal-fluid sciences" can be generalized to a discussion of cross-disciplinary relevance of data acquisition,
- development of more durable communal facilities (reservoirs, firing ranges),
- development of low-volume pressure reservoirs to facilitate reduced muzzle velocity at the higher pressures (>15 psig) necessary to motivate treatment of choked flow across the air cannon valve,
- limitation of student group size to one plus the number of physical subsystem elements to be designed, thus reducing the potential for un(der)employed team members who may be neither building nor modeling, and
- judicious availability of choice in design, whether for velocity measurement circuit elements, velocity-corroborating backstops, data acquisition devices, etc.

Conclusions

A multidisciplinary air cannon project was designed and implemented for use as a five week long module of a Thermal-Fluid Sciences Practicum course at Rowan University. Key principles around which the project was designed included alignment with the concurrent Thermal-Fluid Sciences lecture course, integration of concepts from other mechanical engineering sub-disciplines, open-ended design ambiguity and design decision-making, relatively low resource intensity, relatively low cost, and a "WOW" factor to engage students. The present implementation of this project was broadly successful in appealing to students and meeting our own "design the design project" objectives; however, future implementations may be improved by limiting some student choice and spending more time emphasizing the truly interdependent nature of engineering, regardless of course identification.

Acknowledgements

The authors thank Messrs. Karl Dyer and Charles Linderman for their assistance in developing the air cannon firing range.

References

(1) Sullivan, G., & Hardin, J.-M. (2008). *Using the "WOW" Factor to Actively Engage Engineering Students*. Paper presented at the 2008 ASEE Annual Conference & Exposition, Pittsburgh, Pennsylvania. https://peer.asee.org/4103

(2) History of the Worldwide CDIO Initiative. (2017). Retrieved from http://cdio.org/cdio-history on February 12, 2017.

(3) Andersson, S. B., Malmqvist, J., & Wedel, M. K. (2005). *A Systematic Approach to the Design and Implementation of Design-Build-Test Project Courses*. Paper presented at the 15th International Conference on Engineering Design, Melbourne, Australia. https://www.designsociety.org/publication/23107/

(4) Constans, E., Kadlowec, J., Bhatia, K. K., Zhang, H., Merrill, T., & Angelone, B. (2012). *Integrating the Mechanical Engineering Curriculum Using a Long-term Green Design Project Part 1: The Hybrid Powertrain*. Paper presented at the 2012 ASEE Annual Conference & Exposition, San Antonio, Texas. https://peer.asee.org/21571

(5) Elger, D. F., Beyerlein, S. W., & Budwig, R. S. (2000). *Using Design, Build, and Test Projects to Teach Engineering*. Paper presented at the 30th ASEE/IEEE Frontiers in Education Conference, Kansas City, Missouri. http://dx.doi.org/10.1109/FIE.2000.896572

(6) Malmqvist, J., Young, P. Y., Hallström, S., Kuttenkeuler, J., & Svensson, T. (2004). *Lessons Learned from Design-Build-Test-Based Project Courses*. Paper presented at the 8th International Design Conference, Dubrovnik, Croatia. https://www.designsociety.org/publication/19819/

(7) Shepard, T., Choi, J., Holmes, T. D., & Carlin, B. W. (2015). *The Effect of Project Constraints and Choice on First-year Microcontroller Projects*. Paper presented at the 2015 ASEE Annual Conference & Exposition, Seattle, Washington. http://dx.doi.org/10.18260/p.24860

(8) Rohrbach, Z. J., Buresh, T. R., & Madsen, M. J. (2012). Modeling the Exit Velocity of a Compressed Air Cannon. *American Journal of Physics*, *80*(1), 24-26. http://dx.doi.org/10.1119/1.3644253

(9) Supah-Style Pneumatic Cannon Valve. (2003). Retrieved from http://srjcstaff.santarosa.edu/~spud/ on February 12, 2017.

(10) Mascaro, D. J., & Mascaro, S. (2015). *An Integrated Project-Driven Course in Computer Programming for Mechanical Engineering Students*. Paper presented at the 2015 ASEE Annual Conference & Exposition, Seattle, Washington. http://dx.doi.org/10.18260/p.23533

(11) Najafi, F., Jenner, K., & Jayasekaran, S. (2009). *Civil Engineering Introduction To Freshman Engineers*. Paper presented at the 2009 ASEE Annual Conference & Exposition, Austin, Texas. https://peer.asee.org/4775

(12) Osta, A., & Kadlowec, J. (2016). *Hands-on Project Strategy for Effective Learning and Team Performance in an Accelerated Engineering Dynamics Course*. Paper presented at the 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana. http://dx.doi.org/10.18260/p.25444

(13) Pierson, H., & Suchora, D. (2004). *First Year Engineering Curriculum At Youngstown State University*. Paper presented at the 2004 ASEE Annual Conference, Salt Lake City, Utah. https://peer.asee.org/14099

(14) Shepard, T. (2013). *Implementing First-Year Design Projects with the Power of Choice*. Paper presented at the 2013 ASEE Annual Conference & Exposition, Atlanta, Georgia. https://peer.asee.org/19722

(15) Sullivan, G., & Hardin, J.-M. (2016). *Revitalization of an Intro to ME Course Using an Arduino-Controlled Potato Cannon*. Paper presented at the 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana. http://dx.doi.org/10.18260/p.26109

(16) Swagelok. (2007). *Valve Sizing Technical Bulletin* (MS-06-84-E, R4). Retrieved from https://www.swagelok.com/downloads/webcatalogs/EN/MS-06-84.PDF on February 12, 2017.