Tank Depressurization Experiments for the Classroom or Laboratory

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Introduction

American Society for Engineering Education data show that engineering enrollment in U.S. universities has increased by more than 50% over the last ten years, while the number of engineering faculty has increased by only 15% over the same time period (Yoder 2009, 2017). As a result, the average number of students in engineering classrooms has steadily increased, and this increase has occurred at a time when our students enter the classroom with far less experience in the hands-on aspects of engineering. Our challenge as engineering educators is to reach these students in order to prepare them for their future careers as engineers in society.

Students will likely encounter many different teaching styles during their academic careers, and this variety generally adds to their overall educational experience. However, if given a choice, most students would select instructors that use an interactive teaching style. Pomales-Garcia and Liu (2007) found, in a survey of 47 University of Michigan undergraduate engineering students (30 males, 17 females), that students most preferred interactive teaching that included examples, demonstrations, stories, websites, visual displays, group work, competitions and oral presentations. These types of engagement make the classroom experience more enjoyable for the students and can also help the student in learning and retaining engineering content.

There are numerous examples of student engagement through examples and classroom demonstrations in the literature. Smith *et al.* (2005) focused on the pedagogies of classroom engagement, and most particularly cooperative and problem-based learning, and presented suggestions for redesigning engineering classes and programs to include more student engagement. Fluid mechanics has been a popular subject for classroom engagement, both in the laboratory and through classroom demonstrations. Kresta (1998) began using short demonstrations in the fluid mechanics classroom and observed an increase in attendance from 30% to over 80%. Stern *et al.* (2006) developed a hands-on CFE educational interface for graduate engineering courses and laboratories. Fraser *et al.* (2007) used computer simulations to help sophomore students through the more difficult concepts of fluid mechanics. Loinger and Hermanson (2002) used an integrated experimental-analytical-numerical approach in the teaching of fluid mechanics, and student surveys showed that 90% of their students preferred this re-designed class to the traditional lecture class, while also obtaining a better understanding of the engineering fundamentals.

Tank Depressurization

Many examples can be found in the literature where the overpressurization of process equipment, including tanks, led to catastrophic consequences. Just a few of these examples include:

- The June 13, 2013, fatal accident at the Williams olefins plant in Geismar, Louisiana, in which the rupture of a heat exchanger caused a fire and killed two workers (ANSI Technologies SDN BHD 2017)
- The October 13, 1998, explosion inside a 11.4 m^3 (3,000 gal) Hastelloy reactor, as part of the linear alkyl benzene process at Condea Vista plant in Baltimore, Maryland, which fueled a fire that took about two hours to extinguish (Reza *et al.* 2002)

Photographs from the aftermaths of these two accidents are shown in Figure 1. Chemical processing equipment must be designed so that these catastrophes do not happen. Leung (1992) explains how to implement pressure relief by using "capability for latent heat of cooling via boiling" to generate vapor within the reactor, which is vented in a controlled manner from the vessel to maintain the vessel pressure within safe levels. In order to accomplish the mathematical modeling required to design such a system, the following must be accomplished:

1. Perform a mass and heat balance on the reactor contents, which results in differential equations
2. Determine the vapor venting rate from the vessel through pipe, pipe fittings and orifices
3. Solve the differential equations required to predict pressure vs. time within the reactor

Figure 1. Damage from the Geismar Williams Olefins Plant Accident (ANSI Technologies SDN BHD 2017), left, and the Baltimore Condea Vista Plant Accident (Reza *et al.* 2002), right

An experiment involving the depressurization of an 11 gal (0.042 m^3) air tank through a 0.052 in (1.32 mm) sharp-edged orifice was previously developed for laboratory and classroom use (Penney and Clausen 2018) which can serve as excellent training for the venting calculations performed in practice. In addition, the subsequent modeling study required the students to utilize compressible flow equations and perform computer modeling, including the numerical integration of differential equations. The objective of this paper is to describe additions to this simple experiment for the depressurization of the tank through multiple sharp-edged orifices and a Schrader valve which increases the flexibility of using the experiment in the classroom or laboratory. As in the initial experiment, the experimental data from the experiment were compared to computer model predictions.

Experimental

Much of the experimental apparatus and procedures were previously described by Penney and Clausen (2018) but are shown again below for the benefit of the reader.

Apparatus

A photograph of the experimental apparatus is shown in Figure 2, left. The apparatus consisted of an 11 gal (0.042 m^3) Campbell-Hausfeld carbon steel air tank with a maximum pressure rating of 125 psig (8.5 atm above atmospheric) and a calculated actual volume of 11.6 gal (0.044 m^3). The tank was equipped with a ¼ in (6.4 mm) valve to initiate depressurization, a 0-160 psig (0-10.9 atm above atmospheric) pressure gauge and a ¼ in (6.4 mm) brass pipe plug. Although a pressure gauge and stop watch can be satisfactorily used to collect pressure measurements with time, a Measurement Computing data acquisition device, USB-TC-AI, driven by a 2 amp/12 volt source and connected to the USB port of a Dell Latitude E 5510 laptop computer, was used in the collection of pressure vs. time data. Omega TracerDAQPro software was used to display and analyze the data.

To form the sharp-edge orifices, a ¼ in (6.4 mm) brass pipe plug was drilled from both sides; a $\frac{5}{16}$ in (7.94 mm) square bottom drill was used to form the inlet cavity; a ¼ in (6.4 mm) partially square bottom drill was used to form the outlet cavity. The drilled holes formed a 0.01 in (0.25 mm) plate about midway through the pipe plug. This plate was drilled in its center with 1.07 mm (0.042 in), 1.32 mm (0.052 in) and 1.57 mm (0.062 in) diameter drills to complete the three orifices. Figure 2, right, shows a photograph of one the three brass fittings.

Figure 2. Photograph of the Air Tank and Respective Attachments for Venting Data Collection

A ¼ in (6.4 mm) NPT MPT brass air compressor tank fill Schrader valve (identical to an automobile tire Schrader valve) was similarly installed in a brass pipe plug. Figure 3 shows a typical Schrader valve and a cut-away view of a Schrader valve, demonstrating how it is constructed and how it operates. The operating diameter of the Schrader valve used in this experiment is a bit difficult to measure but can be estimated by realizing that the hole through the valve is partially occupied by the pin. This Schrader valve has a measured hole diameter of 2.26 mm (0.089 in) and a measured pin diameter of 1.04 mm (0.041 in). The area of the open space (annulus) between the hole and pin is determined as $\frac{\pi\left(d_{hole}^2 - d_{pin}^2\right)}{4} = \frac{\pi\left(2.26^2 - 1.04^2\right)}{4} = 3.16$ mm^2. The effective diameter, d_{eff}, of the orifice is then $\sqrt{\frac{4A}{\pi}} = \sqrt{\frac{(4)(3.16)}{\pi}} = 2.01$ mm (0.079in).

Experimental Procedure

Prior to experimentation, the desired orifice or the Schrader valve is installed in the system and the tank checked for defects. After the students familiarized themselves with the data acquisition system, the apparatus is ready for data collection. The tank is pressurized to 5.4 atm absolute (65 psig) with shop air. To begin the experiment, the ball valve is quickly opened fully, and pressure is measured and recorded as a function of time. The experiment ends when the tank reaches a pressure of about 1.5 atm absolute (7.5 psig). The experiment is then repeated with the other orifices and the Schrader valve. Finally, the data are downloaded to Excel files for analysis.

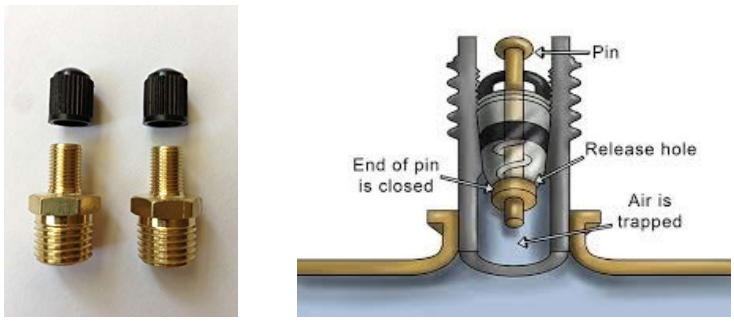

Figure 3. Typical Schrader Valve (left), and a Cut-away View (right)

Safety Concerns

Prior to tank venting, the orifice must be free of obstruction, and the path of the pressurized air must be clear to avoid damage to students and the surroundings. Proper safety equipment for this experiment includes the wearing of safety goggles and long pants.

Model Development

Model development was also shown previously by Clausen and Penney (2018) but is reproduced here for the convenience of the reader. In performing a mass balance on the tank

$$m_i - m_o + m_g = m_a \tag{1}$$

Since the tank has no inlet streams or generation of air, Equation (1) reduces to

$$-m_o = m_a \tag{2}$$

The mass accumulated within the tank, m_a, may be expressed as a differential change in the mass of air in the tank using the continuity equation

$$m_a = \frac{dM}{dt} = \frac{d(\rho_t V)}{dt} \tag{3}$$

The density of the gas can be expressed as follows using the ideal gas equation

$$\rho_t = \frac{P_t(MW)}{RT} \tag{4}$$

Expanding Equation (3) to include the ideal gas equation yields

$$m_a = \frac{d\left(\frac{P_t(MW)V}{RT}\right)}{dt} = \frac{(MW)V}{RT}\frac{dP_t}{dt} = -m_o \tag{5}$$

Finally, the differential pressure change as a function of changing mass flow rate is found by a rearrangement of Equation (5)

$$\frac{dP_t}{dt} = -\frac{m_o RT}{V(MW)} \tag{6}$$

The mass velocity of air leaving the tank may be calculated from the equation (McCabe *et al.* 2005)

$$G = \sqrt{\frac{2\gamma\rho_t P_t}{\gamma-1}}\left(\frac{P_{vc}}{P_t}\right)^{1/\gamma}\sqrt{1-\left(\frac{P_{vc}}{P_t}\right)^{[1-(1/\gamma)]}} \tag{7}$$

The constant γ is the specific heat ratio, which is 1.4 for air.

In Equation (7), the gas density within the tank, ρ_t, and pressure at the vena contracta, P_{vc} , were found using Equations (8) and (9), respectively

$$\rho_t = \frac{P_t(MW)}{RT} \tag{8}$$

$$P_{vc} = P_t(r_c) \tag{9}$$

In these equations, P_t is the absolute tank pressure, MW is the molecular weight of air, R is the ideal gas constant and T is the tank temperature. The parameter, r_c, is the critical pressure ratio, calculated by the equation (McCabe *et al.* 2005)

$$r_c = \left(\frac{2}{\gamma+1}\right)^{\frac{1}{1-\frac{1}{\gamma}}} \tag{10}$$

For air, $r_c = 0.53$. For $\frac{P_a}{P_t} < 0.53$, where sonic velocity occurs, P_{vc} in Equation (7) was set equal to the orifice pressure = 0.53 P_t; for $\frac{P_a}{P_t} > 0.53$, P_{vc} was set equal to atmospheric pressure.
The mass flow from the tank was calculated using the mass velocity (G), the cross-sectional area of the orifice ($Ao = \frac{\pi d^2}{4}$), a dimensionless expansion factor (Y), and the orifice coefficient (C_d)

$$m_o = C_d YGAo \tag{11}$$

The orifice coefficient was found using a linear regression of C_d versus $1 - P_r$ data from Linfield (2014). P_r is the pressure ratio of atmospheric pressure to absolute tank pressure, $\frac{P_{atm}}{P_t}$. The regression results in a fourth-order equation

$$C_d = 0.6219 + 0.0686(1 - P_r) + 0.7955(1 - P_r)^2 - 0.9285(1 - P_r)^3 + 0.2914(1 - P_r)^4 \quad (12)$$

It should be pointed out that Equation (12) is only useful for the sharp-edged orifices, and not the Schrader valve. Thus, C_d is unknown for the Schrader valve and must be determined by best matching (i.e., fit) of the experimental data with the model at assumed values of C_d.

According to the McCabe *et al*. (2005), if the critical pressure ratio, r_c, is less than 0.53 for air, the gas flow is sonic and $Y = 1$. For other r_c values, the expansion factor was computed as follows

$$Y = 1 - \frac{0.41 + 0.35\beta^4}{\gamma}\left(1 - \frac{P_{atm}}{P_t}\right) \quad (13)$$

To determine P as a function of time, the mass flow from the tank is first found using Equations (7) - (13). Matlab was then used to solve the differential equation in Equation (5).

Results and Discussion

Figures 4 and 5 present plots of two of the experimentally measured tank pressures and the model predicted pressures with time. The experimental data are shown as a continuous curve instead of individual data points because the experimental data were obtained from the acquisition system. The average deviations between the experimental data and the model results ranged from 4.7% for the 1.32 mm (0.052 in) orifice to 2.7% for the 1.57 mm (0.062 in) orifice. These relatively "good fits" indicate that the model is adequate for this application. Figure 6 presents a similar plot for the Schrader valve. When using an orifice coefficient, C_d, of 0.71 (found by trial and error with Matlab, based on the best visual fit) the average percent error was 3.8%.

Conclusions/Educational Use and Value

1. The mathematical model predictions fit the experimental data well for depressurization through each of the orifices, with a maximum average variance of the model from the data of 2.7-4.7%.
2. The calculated orifice coefficient for the Schrader valve was 0.71, which is reasonable.
3. The experiment is simple and inexpensive. An air tank costs about $40 and a digital pressure gauge costs about $70; thus, for less than $200, the experimental apparatus can be constructed. Although a data acquisition system is very convenient for recording the *P* vs. *t* data, careful manual recording of the data gives adequate results.
4. Critical and sub-critical nozzle flow occurs in the experiment. Students gain experience handling both.
5. The experiment has been used successfully in both the classroom and laboratory.

6. The modeling involves the solution of a first order differential equation using numerical methods. The computer program involves a logic statement which must be included to handle the transition from critical to non-critical flow as the tank pressure decreases.
7. The model fits experimental data well, which eliminates the frustrating experience for students of explaining why the model does not predict the experimental data.

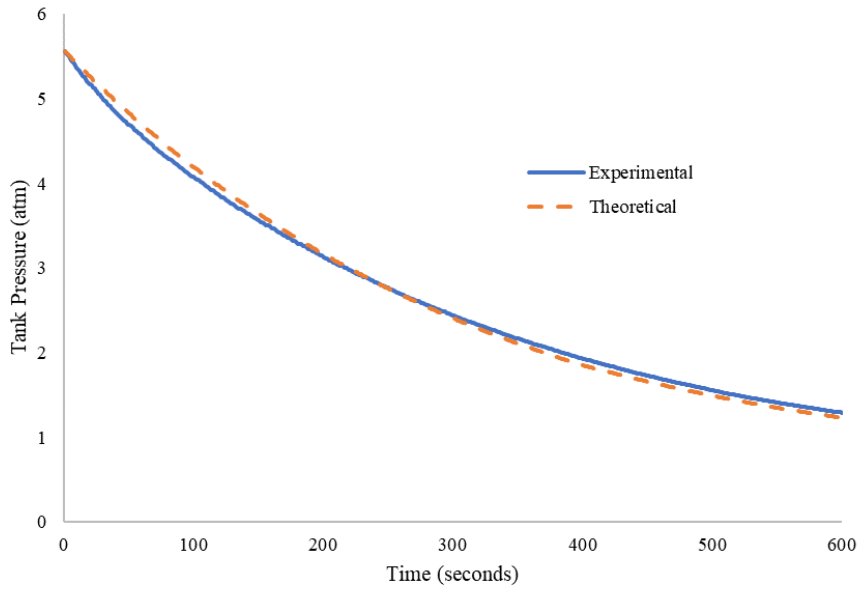

Figure 4. Experimental and Model Results for Tank Depressurization through a 1.32 mm (0.052 in) Orifice

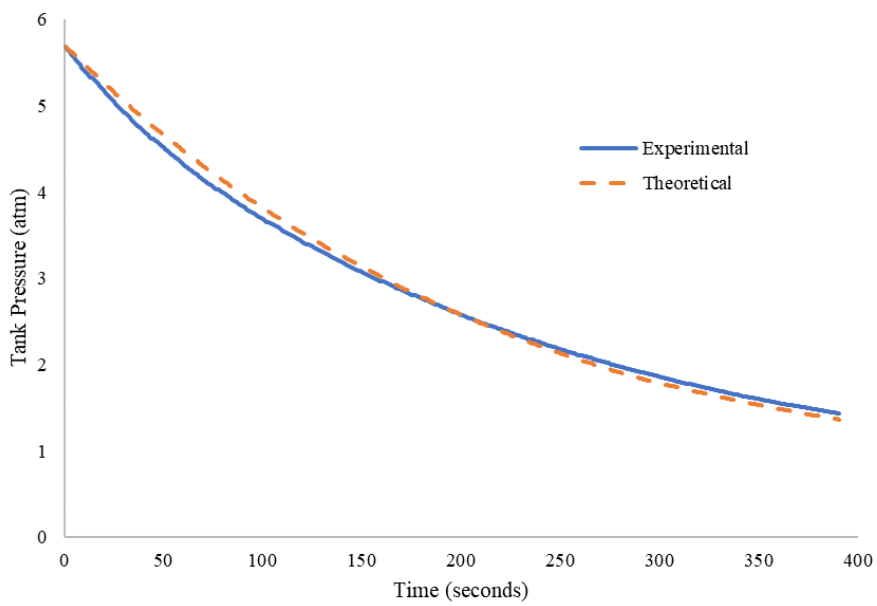

Figure 5. Experimental and Model Results for Tank Depressurization through a 1.57 mm (0.062 in) Orifice

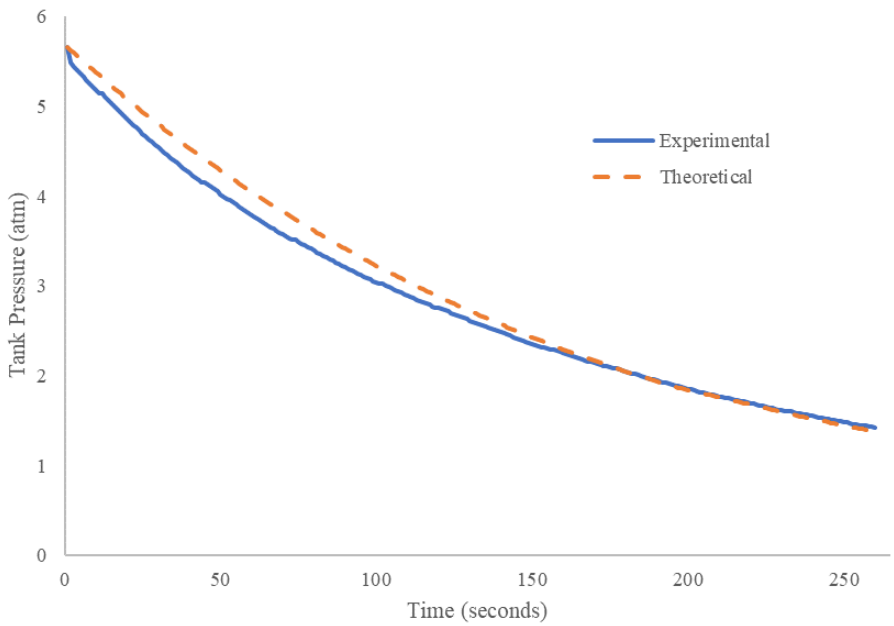

Figure 6. Experimental and Model Results for Tank Depressurization through a 2.01 mm (0.079 in) Schrader Valve with $C_d = 0.71$

Nomenclature (SI units shown)

Latin Symbols

A	Flow area of the Schrader valve, m^2
A_o	Cross sectional area of the orifice, m^2
C_d	Orifice discharge coefficient, dimensionless
d	Orifice diameter, m
d_{eff}	Effective diameter of the Schrader valve, m
d_{hole}	Diameter of hole in the Schrader valve, m
d_{pin}	Diameter of the pin in the Schrader valve, m
$\frac{dM}{dt}$	Change of mass in the tank with respect to time, $\frac{kg}{s}$
$\frac{dP_t}{dt}$	Change in tank pressure with respect to time, $\frac{Pa}{s}$
G	Mass velocity, $\frac{kg}{m^2 s}$
m_a	Mass accumulation within the tank, $\frac{kg}{s}$
m_g	Mass generation within the tank, $\frac{kg}{s}$
m_i	Mass entering the tank, $\frac{kg}{s}$
m_o	Mass exiting the tank, $\frac{kg}{s}$
MW	Molecular weight of air, $\frac{kg}{kgMol}$
P_{atm}	Atmospheric pressure, Pa
P_r	Atmospheric to tank pressure ratio
P_t	Tank pressure, Pa

P_{vc} Pressure at the vena contracta, Pa
R Gas constant, $\frac{cm^3 kPa}{kgmol\,K}$
r_C Critical pressure ratio
T Tank temperature, K
V Tank volume, m^3
Y Gas expansion factor

Greek Symbols
β Diameter ratio
γ Specific heat ratio
ρ_t Air density, $\frac{kg}{m^3}$

Acknowledgment

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Biographical Information

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Ms. Olsen and Mr. Buck were junior-level chemical engineering students when they conducted the experiments and are now rising seniors at the University of Arkansas.

W. Roy Penney

Dr. Penney currently serves as Professor Emeritus of Chemical Engineering at the University of Arkansas. His research interests include fluid mixing and process design, and he has been instrumental in introducing hands-on concepts into the undergraduate classroom. Professor Penney is a registered professional engineer in the state of Arkansas.

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Dr. Clausen currently serves as University Professor and Associate Department Head in Chemical Engineering at the University of Arkansas. His research interests include bioprocess engineering, the production of energy and chemicals from biomass and waste, and engineering education and particularly the enhancement of the K-12 educational experience. Professor Clausen is a registered professional engineer in the state of Arkansas.