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The Hydrostatic Vacuum Tube: a Low-Cost Thermal Fluid Science Laboratory

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Abstract

Students often comment that they benefit from exposure to both analytical and experimental results of concepts discussed in class, especially in the abstract thermal-fluid sciences emphasis area of a Mechanical Engineering curriculum. As educators, we sought to address this deficiency by developing a new test apparatus, the Hydrostatic Vacuum Tube (HVT). In short, a HVT is a vertical tube partially filled with water and a trapped air pocket at the top, initially at atmospheric pressure. One experiment involves opening a valve at the bottom to expose an exit port of sufficiently small exit diameter to prevent backflow of air. Water is collected and measured until the flow stops due to the hydrostatic vacuum created as the air pocket expands. A second experiment (the Draining Tank) can be conducted without trapping the air, by exposing/venting the liquid surface to ambient pressure. The height of the water is measured versus time as the tank drains, driven by a hydrostatic head. Predictive theory is developed and results compared with experiment, with excellent agreement. Key thermodynamics concepts involved are expansion of an ideal gas, hydrostatic pressure, and mass conservation in a control volume. The device could be used in other courses, such as Fluid Mechanics, Engineering System Dynamics, Heat Transfer and Experimental Mechanics. Using the same lab equipment in several courses iteratively will make connections between subject areas. The construction and use of the lab hardware and relevant theory is discussed in this paper. Plans are outlined for assessment of the effectiveness of the lab in improving conceptual understanding of the technical content, broadening the experimental experience, and enhancing the ability to use appropriate technical language when comparing test data and theoretical predictions.

Introduction

Students generally learn more when actively engaged in the classroom, especially in college level STEM courses [1]. Despite the benefits, instructors experience time management and budgetary barriers when creating predominantly active learning events such as a hands-on laboratory activity [2]. For these reasons, the majority of large-enrollment college courses still use traditional passive based lecture environments [3].

At the United States Air Force Academy (USAFA), most of the hands-on experiments in the Applied Mechanics Laboratory - Thermal Fluid Sciences (AML-TFS) curriculum have been mostly purchased “turn-key” devices. For example, a small scale model steam power plant and table-top demos are used for the three heat transfer mechanism. Although these experimental devices have mostly performed as designed, they were initially expensive to procure, can be difficult to set up and coordinate with running a tight class schedule, and have had some reliability issues. Additionally, they can be difficult to scale up to a large number of student groups.

The authors’ goal was to supplement the existing AML-TFS experiments with a new device to demonstrate the hydrostatic vacuum concept. The device will provide the engineering students with hands-on experiences with experimentation, instrumentation, and a way to compare analytical results and experimental results using a relatively simple lab setup. The details in this paper should be sufficient for other universities to set up a similar device at their locations.

The goals of this work are to:

- create a new experimental device in USAFA’s AML-TFS lab which may be used to demonstrate and measure a hydrostatic vacuum,
- use the new experimental device across several courses in the Mechanical Engineering curriculum including but not limited to ME 341 Fluid Mechanics, ME 312 Thermodynamics, ME 325 Engineering System Dynamics, ME441 Heat Transfer and ME 460 Experimental Mechanics to improve students’ experience in comparing experimental and analytical results,
- improve students’ ability to use appropriate technical language when comparing experimental and analytical results.

Description of the Apparatus

Two hydrostatic vacuum devices have been constructed in the USAFA’s AML-TFS Lab. Figures 1 and 2 show photographs of the overall configuration of the first generation device, which was designed and built as part of a guided student Independent Study, referred to as HVT1 (hydrostatic vacuum tube 1). The main section is a 4 foot long, vertical, standard 3 inch diameter PVC pipe with fittings on both ends to allow control of the experiment. The bottom of the pipe is fitted with a reducing union, a tee to which a manometer is attached (a clear vertical tube mounted to the wall), a shut-off valve and a second reducing union to an open barb fitting. A graduated cylinder can be placed under the pipe barb fitting to collect water. The top of the pipe is fitted with a threaded fitting into which a removable plug can be screwed to trap a fixed volume of air. A shut-off valve mounted through the plug (not shown) allows air to vent while the plug is being screwed on in order to set the pressure at the local ambient condition before starting the experiment.

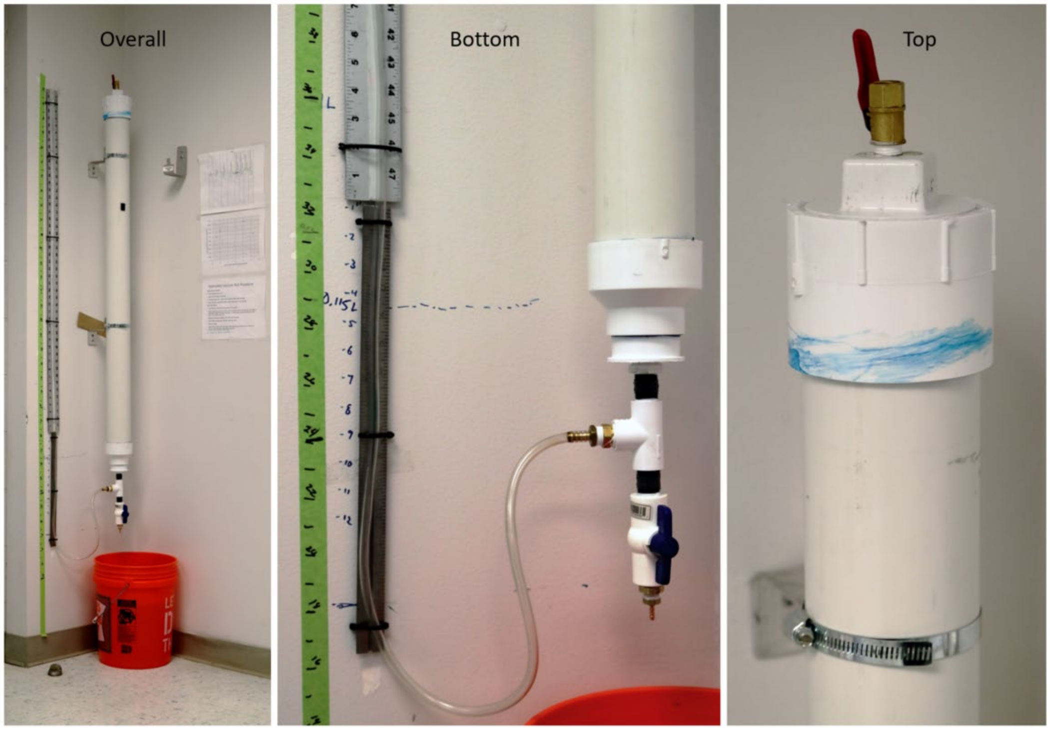

Figure 1. Overall, bottom, and top sections of the first hydrostatic vacuum tube (HVT1). Cost of materials was approximately $50 and all parts were purchased from a local hardware store

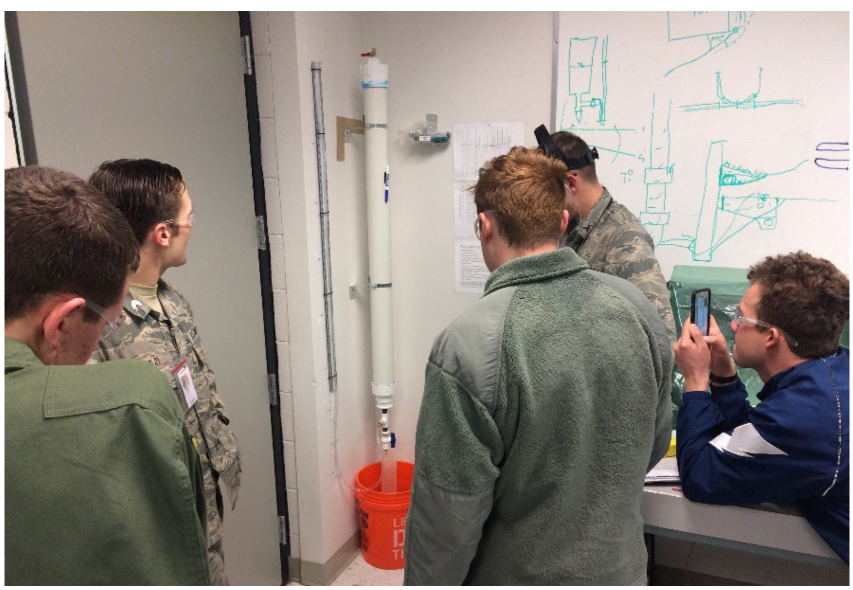

Figure 2. Test in progress conducted by a team of five students. Notice the small footprint of the apparatus, mounted in a corner behind a door.

Figure 3 shows the second hydrostatic vacuum device that was constructed, referred to here as HVT2 (hydrostatic vacuum tube 2). The two devices are similar in construction, except the second generation device has a clear main chamber to allow direct visualization of the water surface level and a second manometer to directly measure the vacuum pressure. The second manometer is not shown in the photos, but would be connected to the top ball valve as shown in the diagram. Additionally, electronic wireless pressure and temperature sensors were installed at the top and bottom for a recent student experiment, but are not discussed here. The main section is also longer and slightly larger diameter - a 6 foot long vertical PVC pipe with a nominal 3.25 inch diameter. The longer the HVT, the greater the vacuum, and the larger the diameter the larger the volume collected (improving sensitivity). If the HVT were sufficiently long (10 m, mounted outside a building or in a stairwell, for example), the free surface of the water could be made to boil at room temperature (similar to a barometer, but with a trapped air at the top).

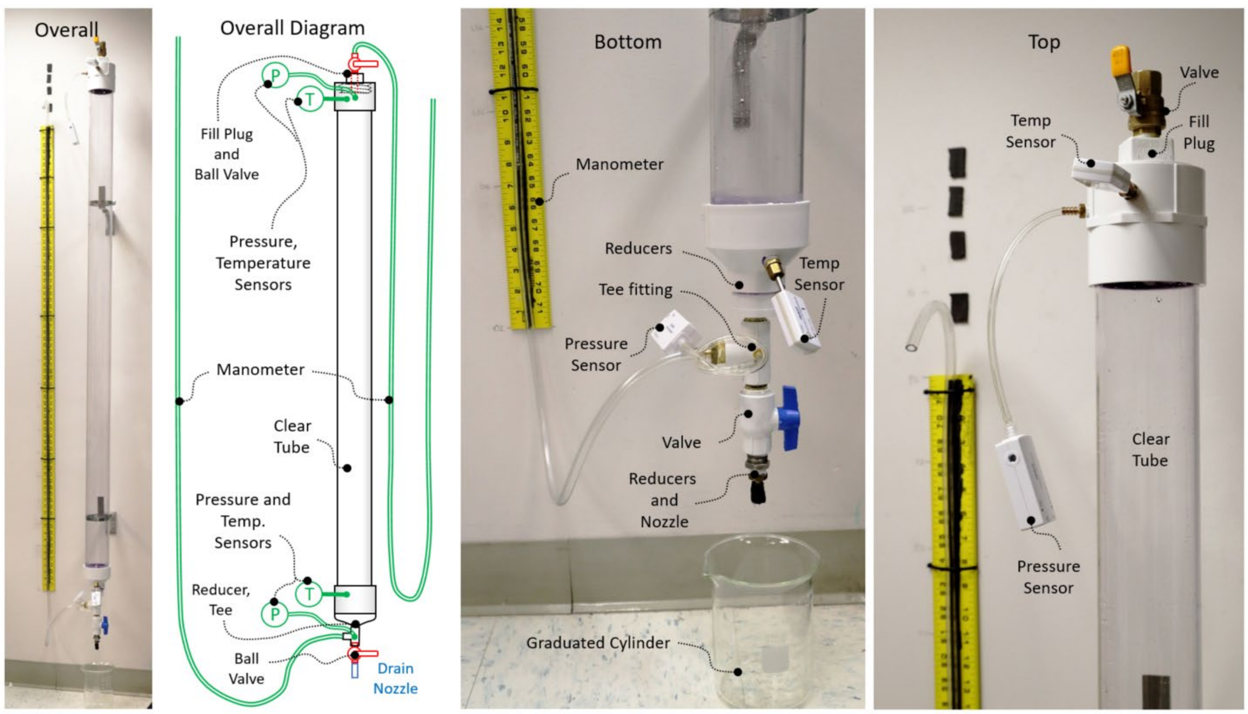

Figure 3. Overall (photo and diagram), bottom, and top sections of the second hydrostatic vacuum tube (HVT2). An additional manometer can be connected to the top ball valve to indicate the vacuum pressure as shown in the diagram (but it is not shown in the photos).

The material costs to construct the generation 2 device is shown in Table 1. The items were sourced from McMaster-Carr but could be readily obtained from other sources.

Table 1. Components, part numbers, and unit price of the hardware needed to construct the second generation (clear chamber) hydrostatic vacuum device (HVT2). Prices are from February 2022.

Part	Part #	Unit price
Polycarbonate tubing (8')	9176T17	$71.81
1ea 3” slip x female adapter	4880K87	$6.82
1ea 3” hex male plug	2389K79	$5.86
1ea ½” ball valve m/f	47865K13	$15.28
1ea 3” x 1 ½” reducer bushing	2389K74	$14.69
1ea ½” threaded tee (f)	4880K154	$4.05
1ea ½” threaded shut-off (f)	4876K11	$12.22
2ea ½” nipples	4677T11	$2.25
¼” clear tubing (8')	5233K55	$5.04
1ea 1 ½” socket pipe plug	4880K846	$2.68
	Total	$142.95

Classroom Demonstrations Prior to Lab

The two hydrostatic vacuum tube (HVT) devices are used to conduct the HVT Lab. The lab is first discussed in the ME312 Thermodynamics course when the Ideal Gas Equation of State, basic hydrostatic equations, and open system mass balances are first introduced. The actual lab is conducted later during the ME431 Fluid Mechanics course after the introduction of remaining needed basic principles including Bernoulli equation and friction in internal flows. Pressure, fluid statics, manometers, and the conservation of mass are common to Thermodynamics and Fluid Mechanics courses.

A classroom demonstration representing two classic “bar tricks” or “parlor tricks” can serve as an introduction to this lab. In the first trick a bottle with a hole in the bottom is demonstrated to be leakproof, despite the hole. Prior to class, the instructor will drill a small hole in the bottom of a common plastic water bottle that has a sealable cap. This can be achieved in various ways, such as using a drill, a pocket knife, or a flame heated paper clip tip. Next, the instructor fills the bottle with water. During filling with the top open water will leak out the bottom hole, but as soon as the bottle is capped the leak will stop. The instructor should avoid squeezing the sides once the bottle is capped. The instructor will come to class with the altered bottle and a container to collect water (and a towel, just in case). During class, the instructor will hand the bottle and container to a student volunteer and ask them to unscrew the lid, holding the neck (and make sure there are no electronics or important papers around). A fine jet of water will flow. Then instruct them to screw the lid back on. The leak will stop within a few seconds. At this time, the instructor can ask students if the flow leak from the bottom stops faster with the bottle nearly full of water, nearly empty of water, or somewhere in the middle.

This could be a good time to divide the class into small teams (Think/Pair/Share activity) and ask them to discuss amongst themselves for just a few minutes. Then ask for answers. The key here is to stimulate the students to think about why, even if they can't articulate it just yet. Although the instructor should allow the students to verbalize their own answer, an explanation is that a partial vacuum is created in the trapped air pocket, whose magnitude can be determined by the hydrostatic head between the water surface and ambient at the exit hole.

The second trick is familiar to any elementary student – the drinking straw pipette effect. This demonstrates a hydrostatic vacuum using a straw, where fluid can be trapped by dipping the bottom of the straw into a liquid, then sealing the top with a finger. Subsequent removal of the straw from the liquid will move the trapped liquid to a new location where it can be released by breaking the top seal. An extension of this demonstration may be done with progressively larger diameter straws or pipes to reveal that beyond a certain diameter the fluid will fall out of the bottom, because surface tension can no longer maintain a defined liquid free surface at the bottom.

Experimental Procedures

Two main experiments can be conducted with the HVT, each in a short period of time (15 minutes); one with the top plug secured and closed, creating a pocket of trapped air (Hydrostatic Vacuum Experiment), and one with the top plug off (or venting valve open) and the water surface exposed to atmosphere (Draining Tank Experiment). Lab procedures for both experiments are described below:

Experiment I: Hydrostatic Vacuum Test:

1. Ensure the "on/off" shut-off valve on the bottom of the main pipe is in the closed position and remove (unscrew) the plug at the top.
2. Pour a measured initial amount of water into the top of the pipe (the amount is assigned by the instructor to each 2-3 member student team). Start with 0.5 liters of initial water added (or the minimum volume below which all the water drains which depends on the precise implementation). Observe the level of the manometer as water is added (it follows the level in the HVT) and record the final value.
3. With the venting valve open on the top plug, screw the top plug back on ensuring that it is flush with the top of the threaded fitting. Opening the venting valve on the top plug eliminates air compression as the plug is screwed on the main tube.
4. Close the venting valve in the top plug to seal the main chamber.
5. Place the graduated cylinder below the spout barb to collect the water.
6. Open the "on/off" valve on the bottom of the main pipe to release water from the chamber and wait for the water to stop flowing from the spout. Observe the manometer as the water drains (it falls rapidly, while the water level in the HVT moves very little, in practice).
7. Record the amount of water collected and plot the point on the sheet provided.
8. Repeat the procedure with a different volume of initial water added. Each class should record data for ~10 data points between 0 and 5.5 liters of initial water added (adjust the minimum and maximum for different size HVTs.

A typical sample of raw data taken from HVT1 for the hydrostatic vacuum experiment is shown in Figure 4. A good practice to develop is to plot the data as it is being taken. This is accomplished in step 7 by providing a blank set of axes (like Figure 4 without data) at the start of the lab.

An alternative implementation to involve more students is to rotate between student teams, with each team assigned a different initial volume and then compile the results of all teams. This "round-robin" class period would involve creating other activities (other labs or practice workshops) that students would rotate through.

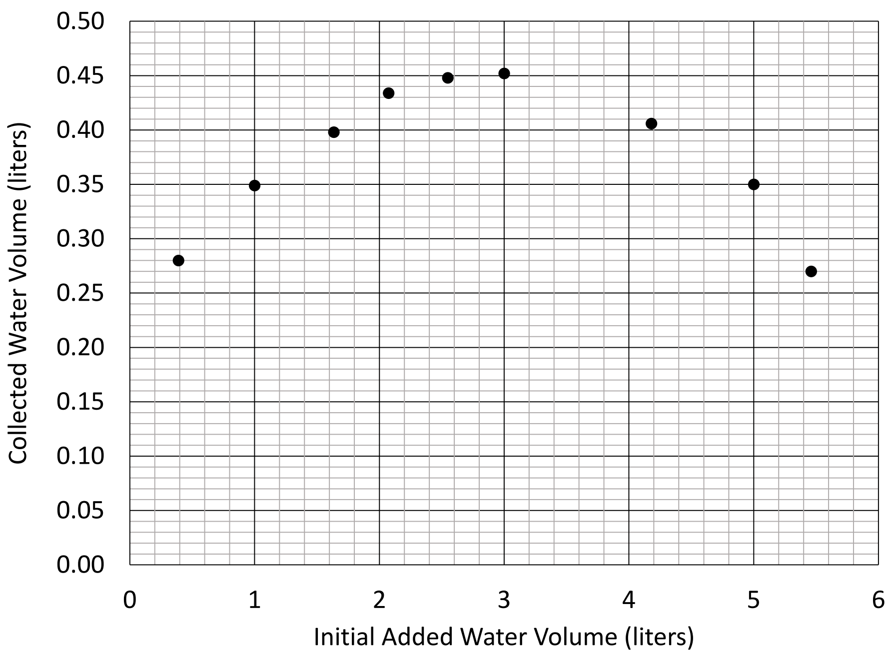

Figure 4. Sample plot of raw data taken from HVT1 during shakedown testing of Experiment I (Hydrostatic Vacuum Experiment). Collected water from test is plotted against the initial water charged in the system.

Experiment II. Draining Tank Experimental Procedures:

This mode requires a minimum of 2 experimentalists to collect data.

1. Ensure the shut-off valve on the bottom of the pipe is in the closed position and remove the plug at the top.
2. Pour a known volume into the top of the pipe until the manometer lever reaches its maximum point without overflowing the pipe.
3. Place the bucket under the spout.
4. Start a stop watch. One experimentalist will watch the water level and call out height values at it crosses (the manometer height corresponds with the water level/volume remaining in the main tube). The other experimentalist will note the time when the height is called and record the data until the water has been completely discharged from the

tank. Note - a scale and data logging system can also be used to measure the mass flow rate of the outflow.

A typical sample of raw data taken from HVT1 for Experiment II (Draining Tank Test) is shown in Figure 5. This plot may appear linear at first glance, but has a clear concave up curvature. The curvature would be more apparent if the test could be conducted until the water level reached the exit (which is 21 cm below the base of the main tube in this embodiment). The basic set-up could be redesigned to allow complete drainage.

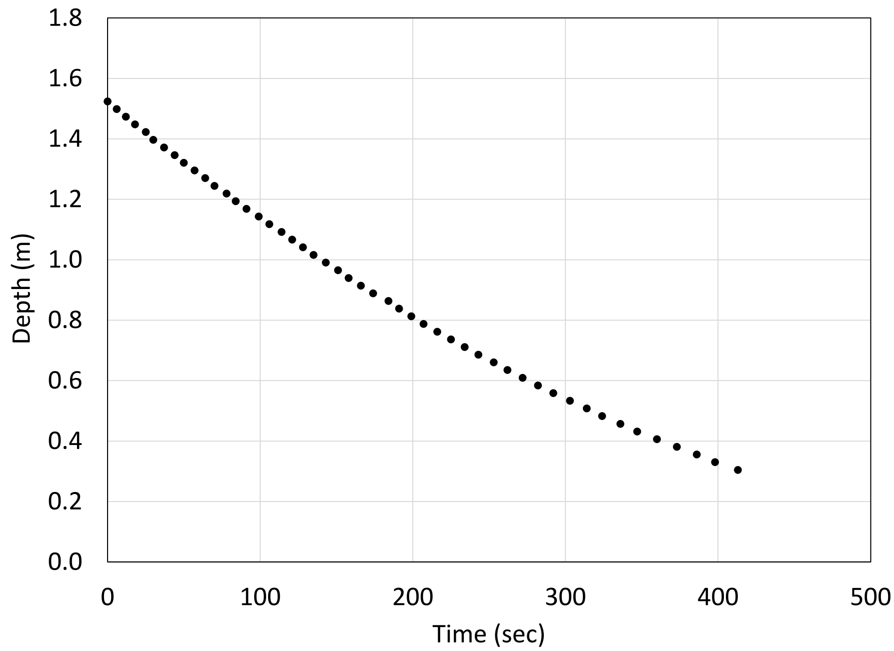

Figure 5. Sample plot of raw data taken from HVT1 during shakedown testing of the Draining Tank Experiment. Water depth is plotted against time.

Basic Theory for Experiment I: Hydrostatic Vacuum Test

Conducting the lab does not require understanding the theory behind it. Therefore, the basic theory of hydrostatic vacuums can be discussed with the students either prior to or after conducting the lab. Depending on their natural learning style, some students will be in a better position to follow the theory if they have conducted experiments first. This is more of an inductive approach [4, 5]. Others will benefit from seeing derivations first (more deductive learning style).

A schematic of the experimental configuration is shown in Figures 6 and 7. Three volumes are needed to conduct a precise analysis: the clearance volume (V_c), the pipe volume (V_p), and the base volume (V_b). These could be measured by the instructor and values given to the students, or more time could be allotted for students to measure them.
There is some clearance volume (V_c) associated with the fittings at the top which represents void space created between the plug (after it is secured) and the top of the main pipe. This volume

can be measured by filling the inverted top assembly with water. The pipe itself has a volume $V_p = AL = \frac{\pi D^2}{4} L$ where D is the inner diameter and L the length of the pipe section. A is the cross-sectional area. A sample of piping can be passed around class with calipers to demonstrate the difference between nominal and actual pipe diameters. The volume of water below the pipe section is called the base volume, V_b, and represents volume in the fittings below the pipe. This volume can be measured by filling the base assembly with water to the bottom of the tube.

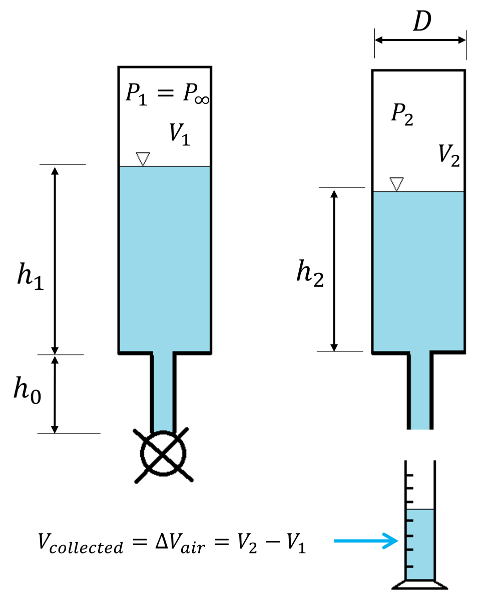

Figure 6. Schematic of experimental arrangement at the initial (1) and final states (2).

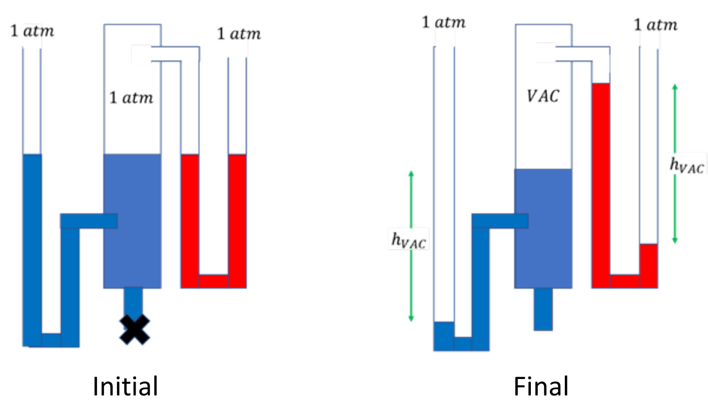

Figure 7. Initial and final illustration of a HVT with two manometers. HVT1.

The total volume is the sum of the three:

$$V_{total} = V_c + V_p + V_b$$

For a given experiment, the device is filled with a pre-determined quantity of water (V_{added}), which defines the initial height of the water column.

The initial volume of trapped air (V_1, after the plug is inserted) depends on the volume of water added initially, the main experimental control variable. That is:

$$V_{total} = V_1 + V_{added}$$

The initial height of the water column in the pipe can be expressed as

$$h_1 = \frac{V_{added} - V_b}{A}$$

The effective cross-sectional area (A) should include both that of the tube and the manometer for precise measurements. Neglecting the manometer here would introduce a systematic error (and an opportunity to explain that). The final height of the water column can be related to the initial height and the change in volume (ΔV) which is equal to the volume of water collected:

$$h_2 = h_1 - \frac{\Delta V}{A}$$

The pressure of the water just above the valve is the hydrostatic pressure, $P_1 + \rho g(h_1 + h_0)$ where ρ is the density of liquid water and $h_0$is the fixed height of the base of the tube above the exit (21.6 cm for HVT1). There is also a hydrostatic pressure distribution in the air, but that is neglected, since the air density is much less than that of liquid water. That is, as is typically done for analyses that involve air in a container, the pressure in the air cavity is considered to be uniform, while the pressure in the liquid is governed by a hydrostatic distribution at the initial and final states. The pressure and temperature of the trapped air would rise slightly as the plug is screwed in if there was not a vent in the top plug. The temperature is assumed to achieve thermal equilibrium with the environment in subsequent analysis, although during the process the temperature would tend to decrease due to the expansion work of the trapped air. A separate heat transfer analysis was conducted for HVT1 that shows that thermal equilibrium is effectively attained by the end of the test.

When the valve at the bottom is opened, the pressure at the discharge (the end of the spout or nozzle) suddenly drops from its initial hydrostatic value to ambient pressure, and a gravity driven flow commences. As it does, the trapped air pocket expands (volume increases). The pressure and temperature decrease as work is done by the air on its environment. Eventually, however, a new stable equilibrium state is reached where motion ceases, the temperature becomes ambient and the pressure at the exit of the spout is ambient. The pressure of the air pocket is a partial vacuum defined by the hydrostatic distribution in the water, that is, a hydrostatic vacuum is created, of magnitude $P_2 = P_\infty - \rho g h_2$ as shown in Figure 6.

For the lab write-up for Experiment I, students should include experimental results of the collected water during the creation of the hydrostatic vacuum as a function of the initial water added for the USAFA HVT test stand. Students make a plot showing Initial Added Water Volume (liters) on the x-axis vs. Collected Water Volume (liters) on the y-axis. They are asked to write a report and provide analysis and conclusions based on observations such as where the collected volume exhibits a peak.

Students are then challenged to compare their plot to the theoretical values from two different models (detailed below), both involve application of a hydrostatic pressure principle and ideal gas properties. The instructor would decide how much theory to develop in class before the lab. Students are asked plot experimental results on the same graph as the two theoretical models. A third model (a transient heat transfer analysis) is outlined here and the results presented for the purpose of demonstrating the nature of the process.

Model A: Neglect Elevation Change

The first theoretical model captures the key controlling physics with a simple result. The ideal gas law can safely be applied to the trapped air, with humidity effects neglected. Provided that some liquid water remains in the cylinder in the final state, the mass of air (times the gas constant) is the same for both initial and final states (and any intermediate state):

$$M_{air}R = \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = \frac{PV}{T}$$

By taking the derivative, using the chain rule, and dividing by PV/T, a differential form of the ideal gas law is:

$$\frac{dP}{P} + \frac{dV}{V} - \frac{dT}{T} = 0$$

This form is exact for a differential change. By considering a finite change, an approximation is:

$$\frac{\Delta P}{P} + \frac{\Delta V}{V} = \frac{\Delta T}{T} = 0$$

While the temperature of the air may change during the process (there is expansion work), eventually, it reaches thermal equilibrium with the environment. That is:

$T_2 = T_1 = T_\infty$ or $\Delta T = 0$

Therefore, the fractional change in air pressure equals the negative of the fractional change in volume:

$$\frac{\Delta P}{P} = -\frac{\Delta V}{V}$$

The change in volume of the air is equal to the volume of water collected (the desired quantity), that is, $\Delta V = V_{collected}$. Therefore, using the initial (pre-plug) state as the basis:

$$V_{collected} = \Delta V = -\frac{V_1\,\Delta P}{P_\infty}$$

This preliminary result shows that the volume of water collected is proportional to the vacuum created (ΔP), and to the initial volume of air. If the initial volume of starting water in the tube is small, the volume of air is large, but the hydrostatic vacuum created is small. On the other hand, if the initial volume of starting water is a large percentage of the total volume, the hydrostatic vacuum is large, but the volume of air is small. This trade-off explains why the collected volume peaks for water volumes that are about half of the total volume, as observed experimentally and predicted by theory (as will be shown shortly).

After the valve is opened and the final equilibrium state is achieved, the final air pressure will be determined by a hydrostatic relationship across the water, with the bottom of the water free surface being at atmospheric pressure. That is:

$$P_2 = P_\infty - \rho g(h_2 + h_0) \approx P_\infty - \rho g(h_1 + h_0)$$

This last approximation simplifies the analysis because the change in pressure is determined by the initial condition. That is, the initial height defines the magnitude of the hydrostatic vacuum produced. This behavior will be apparent when conducting the lab, during which the change in the water level is not large. Model B will relax that assumption, resulting in a more complicated analysis (yet still analytical), but obscuring the controlling physics.

The volume of water added is simply related the height by:

$$V_{added} = V_b + h_1 A$$

The change in pressure, is:

$$\Delta P = \left(P_\infty - \rho g(h_1 + h_0)\right) - P_\infty = -\rho g\left(\frac{V_{added} - V_b}{A} + h_0\right)$$

The initial volume of air is related to the volume of water added by:

$$V_1 = V_{total} - V_{added}$$

$$V_{collected} = \frac{\rho g}{P_\infty}(V_{total} - V_{added})\left(\frac{V_{added} - V_b}{A} + h_0\right)$$

This is the desired result, a closed-form prediction of the volume of water collected for an input volume of water added initially. A useful form that introduces the fraction of volume added is:

$$V_{collected} = \frac{\rho g V_{total}^2}{P_\infty A}\left(1 - \frac{V_{added}}{V_{total}}\right)\left(\frac{V_{added}}{V_{total}} - \frac{V_b}{V_{total}} + \frac{h_0 A}{V_{total}}\right)$$

Expressing the result in terms of linear dimensions (instead of volumes):

$$V_{collected} = \frac{\rho g A L^2}{P_\infty}\left(1 - \frac{h_1}{L}\right)\left(\frac{h_1}{L} - \frac{V_b}{V_{total}} + \frac{h_0}{L}\right)$$

This relationship shows that there is a maximum volume collected when $\frac{h_1}{L} = \frac{1}{2}\left(1 + \frac{V_b}{V_{total}} - \frac{h_0}{L}\right)$, which can be shown by setting the derivative with respect to h_1 to zero. The maximum occurs when the added water is a little less than half the total volume (exactly halfway when $V_b = h_0 = 0$).

To reiterate, there is a trade-off. A large initial air volume (small h_1, i.e. a small quantity of added water) favors a large volume of water collected, but that results in a low hydrostatic vacuum. On the other hand, a large added water volume results in a large hydrostatic vacuum, but the initial volume of air is small and it takes a small volume change to achieve the hydrostatic vacuum.

Model B: Accounting for Elevation Change

In this model, the final hydrostatic pressure is based on the final height, not the initial height (as approximated in model A). The basis for the calculation is a simple ideal gas law expression of the trapped air at the initial point before the plug is inserted, and the final state with the hydrostatic vacuum.

$$M_{air}R = \frac{P_\infty V_1}{T_\infty} = \frac{P_2 V_2}{T_2}$$

Thermal equilibrium is assumed, and therefore the temperature cancels. The final volume is expressed as the initial volume plus the volume change ΔV, which is the desired quantity. The final pressure is a hydrostatic relation. That is:

$$P_\infty V_1 = \left(P_\infty - \rho g\left(h_1 - \frac{\Delta V}{A} + h_0\right)\right)(V_1 + \Delta V)$$

The final height has been related to the initial height plus the change, that is, $h_2 = h_1 - \Delta V/A$. Expanding all terms and rearranging into the form of a quadratic equation for the volume change:

$$\left(\frac{\rho g}{A}\right)\Delta V^2 + \left[P_\infty + \rho g\left(\frac{V_1}{A} - h_1 - h_0\right)\right]\Delta V - \left[\left(P_\infty + \rho g(h_1 + h_0)\right)V_1\right] = 0$$

To manipulate into a form more suitable for the quadratic formula, all terms are multiplied by *A/(2ρg)*:

$$\frac{1}{2}\Delta V^2 + \left[\frac{P_\infty A}{2\rho g} + \frac{V_1}{2} - \frac{A}{2}(h_1 + h_0)\right]\Delta V - \frac{A}{2}(h_1 + h_0)V_1 = 0$$

With "a" = ½ from the quadratic formula, and recognizing the positive root gives the only physically positive result, the collected volume is:

$$V_{collected} = \Delta V = -b + \sqrt{b^2 - 2c}$$

where:

$$b = \frac{P_\infty A}{2\rho g} + \frac{V_1}{2} - \frac{A}{2}(h_1 + h_0)$$

$$c = -\frac{A}{2}(h_1 + h_0)V_1$$

Figure 8 shows the results of both models and the experimental data for the HVT1 set-up. There is a slight shift between models, and excellent agreement between the experiment and model B. Analyzing the data accurately requires close attention to details, such as using the actual clearance and base volumes, which should be measured independently, and a decision as to whether to incorporate the effect of the manometers (a form of loading error that can be accounted for with proper interpretation). All these effects were included in the analysis of the case study shown in Figure 8.

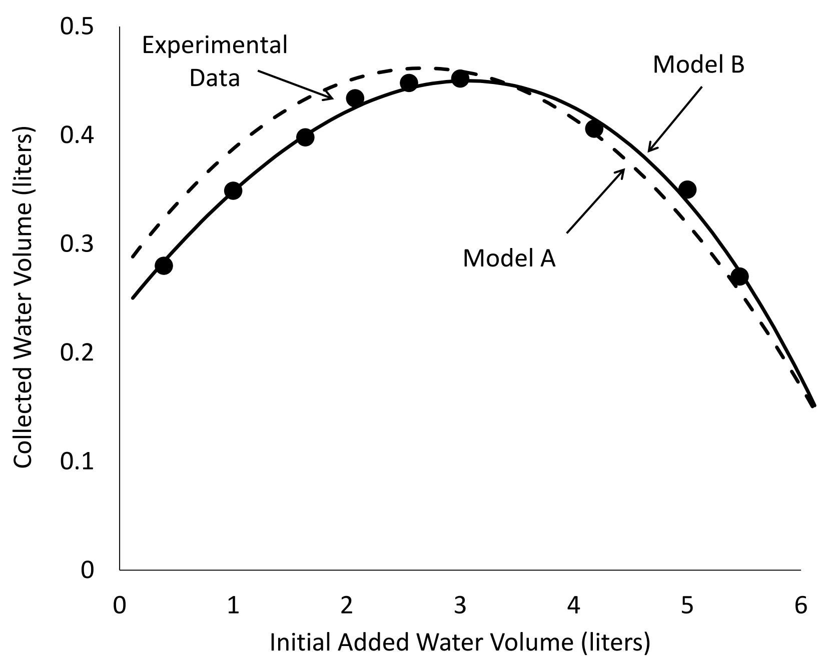

Figure 8. Model A (dashed) and Model B (solid) predictions with Experimental Data (filled data points) of Collected Water Volume vs. Initial Added Water Volume.

Model C: Numerical Simulation of Transient Process

Models A and B involve relating the initial and final states only, and do not attempt to address the details of the process as it occurs. There are important thermodynamic principles that are not apparent in that case. For example, the expanding air pocket does work on its environment, which tends to lower the air pocket's temperature, and then heat transfer will occur between the surrounding room air environment and the pocket. Models A and B assumed thermal equilibrium without justification. The details of the analysis are not developed here, but follow those developed in [5, 6] or any standard heat transfer textbook. It also involves Fluid Mechanics principles (the energy equation for internal flows).

An energy balance applied to the air (treated as a control mass) is:

$$\frac{dU}{dt} = \dot{Q}_{in} - \dot{W}_{out}$$

where,

- $U - U_{ref} = Mc_v(T - T_{ref})$ is the internal energy of the control mass relative to a reference temperature,
- $\dot{Q}_{in} = hA_s(T_{walls} - T)$ is the rate of heat transfer into the mass, with a convection coefficient (h), an exposed surface area to the walls of the container (A_s) at a temperature T_{wall}.
- $\dot{W}_{out} = P\frac{dV}{dt}$ is the rate of work done by the gas.

In order to complete the analysis, the energy equation for internal flows applied between the free surface (at pressure P, elevation $h+h_0$) and the exit jet (at atmospheric pressure, zero elevation, but with kinetic energy) is:

$$\frac{P_\infty}{\rho} + \frac{V_{exit}^2}{2}\left(1 + f\frac{L}{d_{exit}}\right) = \frac{P}{\rho} + g(h - h_0)$$

where frictional effects in the exit tube are included with a friction factor (the barb fitting internally is a cylinder of length L with diameter d_{jet}). Mass conservation as derived previously is also required to relate velocity of the exit jet to the change in volume of the air pocket.

Results of a simulation for HVT1 with the initial volumes of air and water equal are shown in Figure 9. The event takes approximately 45 seconds, during which time the volumetric flow rate gradually decreases as the magnitude of the vacuum increases (top left graph). The temperature decreases sharply initially due to the expansion of the air pocket, but only on the order of 1°C. As time proceeds, heat transfer from the walls is able to bring the air pocket back to near ambient by the end of the event. The Reynolds number of the flow in the hose barb (bottom left) shows that the flow in the straight section of the hose barb (length 1.6 cm, diameter 0.23 cm) is likely turbulent at the start of the vent, and becomes laminar near the end as the drain velocity slows. The bottom right plot shows the individual terms in the energy equation, which shows initially a significant change in stored internal energy in the first 10 seconds. After that, the work of expansion and heat transfer rates are balanced (isothermal behavior).

The theory and applications required to simulate these results required more advanced theory, and could be developed in upper level courses (such as heat transfer).

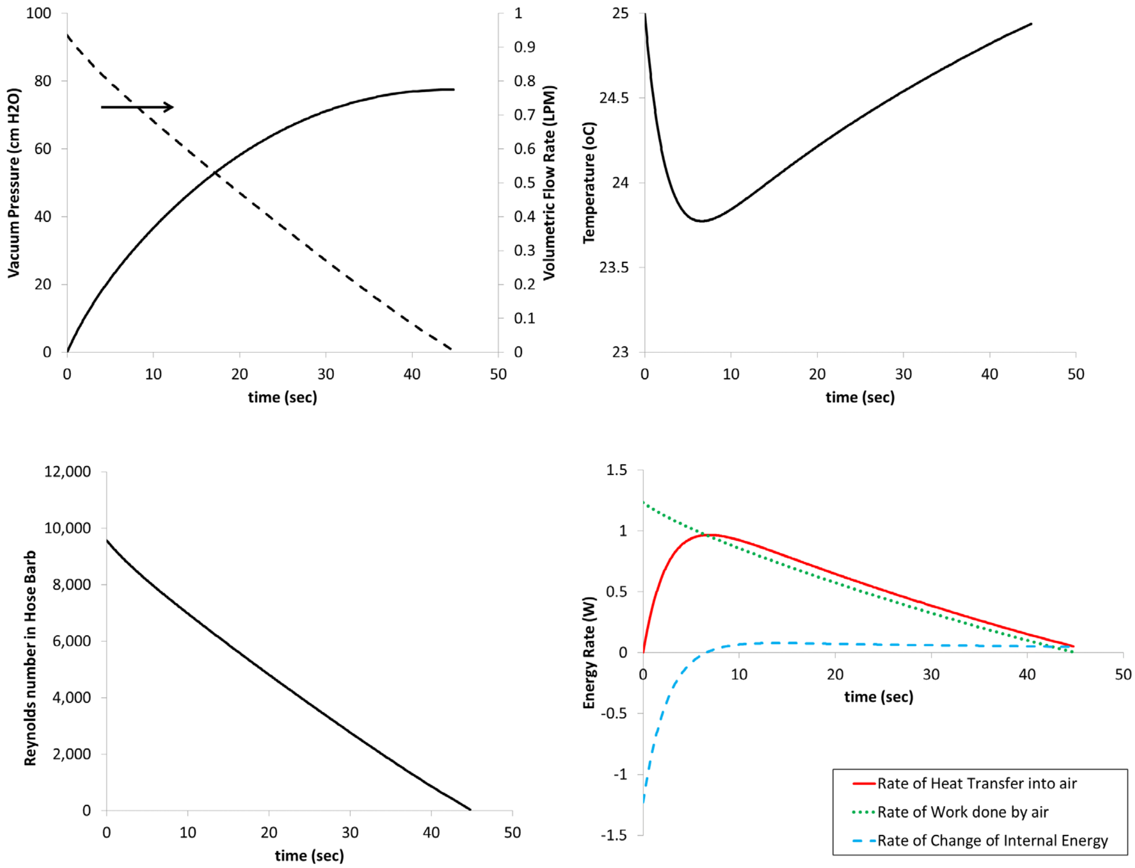

Figure 9. Results of a numerical simulation of a transient HVT event. Pressure (expressed as a vacuum in cm of H_2O) and volumetric flow rate in top left, temperature in top right, Reynolds number in exit barb in bottom left, and energy rate terms in bottom right.

Basic Theory for Experiment II: Draining Tank Experiment

The goal of the analysis of the draining tank is determine the relationship between the depth of the water column and the velocity of the exit jet. Experimentally, this will involve data analysis, since the raw data is in the form of depth vs. time (Figure 5), and a numerical derivative of discrete data must be conducted to obtain velocity. The most natural first attempt is to take a simple forward difference first order derivative of the raw data to obtain the velocity, that is, for data point 'i':

$$V_{jet(i)} = \frac{h_{(i+1)} - h_{(i)}}{t_{(i+1)} - t_{(i)}}$$

The data of Figure 5 appears to have low scatter, and it will be apparent that this method of data analysis introduces significant scatter. No further attempts to smooth the data are made here, but there are several ways to do so, which is an opportunity to develop signal processing theory.

Several basic theories of fluid mechanics are discussed with the students prior to conducting the lab. These include pressure and fluid statics, the conservation of mass, steady versus unsteady flow, flow patterns and flow visualization, and Bernoulli's principle. Experiment II can be approximated as a discharge of water from a tank problem, which is covered in most undergraduate fluid mechanics textbooks [7].

The conservation of mass relation for a control volume undergoing any process is given in rate form:

$$\frac{dM_{CV}}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

If a moving control volume (CV) is defined with the top surface coincident with the free surface of the liquid, and the bottom at the plane of the exit jet, then the mass stored in the CV is:

$$M_{CV} = \rho V_{water} = \rho(V_b + A_{tube}h)$$

The mass flow rate in is zero (typically), and the mass flow rate out is related to the exit flow conditions. The mass balance becomes:

$$\rho A_{tube}\frac{dh}{dt} = -\rho V_{exit}A_{exit}$$

The exit velocity for circular tube and exit jets of diameters d_{tube} and d_{jet} is therefore:

$$V_{exit} = \left(\frac{d_{jet}}{d_{tube}}\right)^2 \frac{dh}{dt}$$

The results from the shakedown test are shown in Figure 9, along with a plot of the prediction of inviscid theory (Bernoulli's equation) which is not developed here formally. The result is that the velocity of the exit jet is the same as what would be obtained from an object dropped in free fall from a height h. The main experimental result here is obtained from mass principles only.

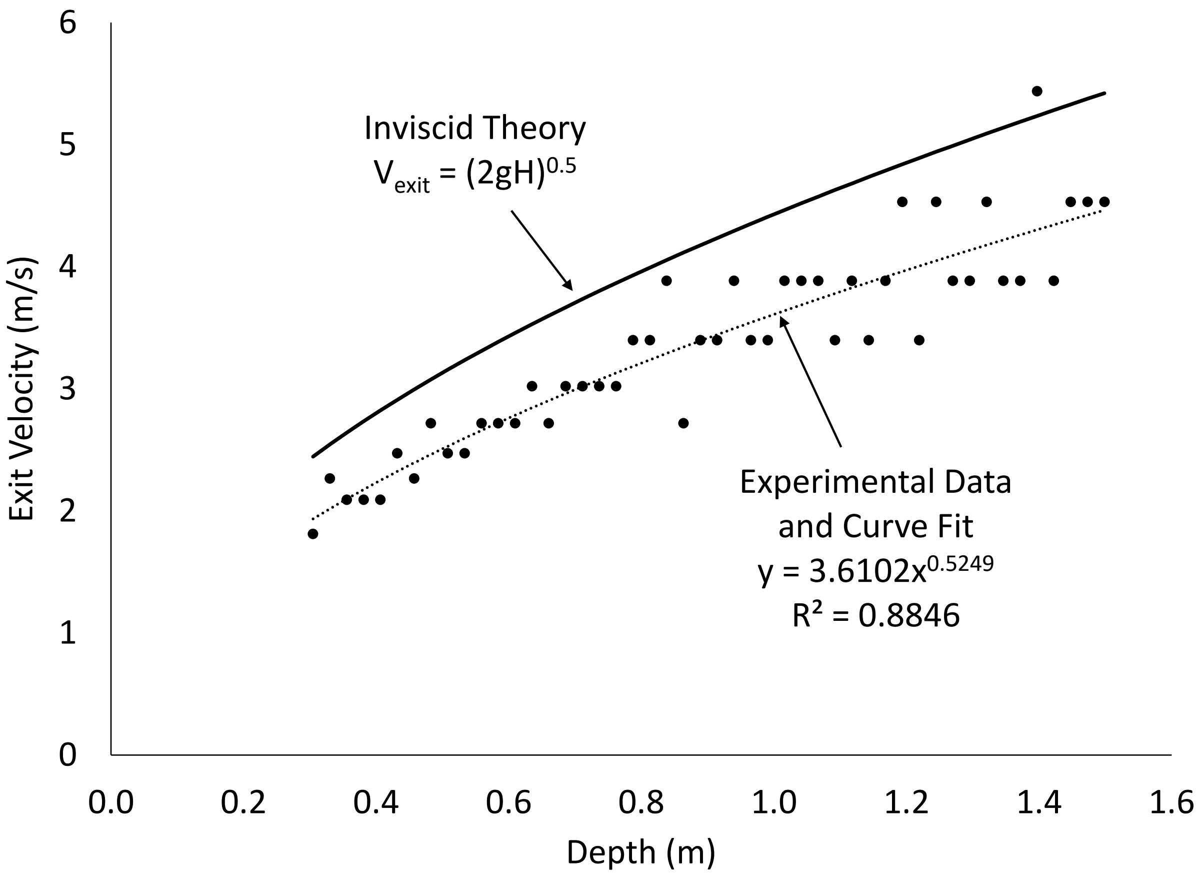

Figure 9. Exit velocity plotted against water depth for the draining tank. A power law fit is applied to the data (informed by theory) and the prediction obtained by inviscid theory (Bernoulli's Law) is also shown.

Using the Hydrostatic Vacuum Devices for Other Courses

In addition to our Thermodynamics and Fluid Mechanics courses, we have also used the Hydrostatic Vacuum Devices in other courses. One example is in our ME325 Engineering System Dynamics course which includes modeling, analysis, and design of multidomain engineering systems. A homework problem is assigned with similar geometry to the hydrostatic vacuum device (generation one, i.e. HVT1) is used in the course as shown in Figure 10. The problem reads: "A tube is pressurized with an initial pressure $P = P_o$. The tank has a uniform circular cross section, A. Assume all the tank dimensions, orifice parameters, and fluid properties are known. As fluid drains from the tank, the pressure above the fluid decreases according to $P = \frac{V_0}{V} P_0$ (this assumes the gas above the fluid behaves as an ideal gas and the process is isothermal). Atmospheric pressure acts at the outlet." Students are given the geometry and discharge coefficient, and asked to:

a) Derive the differential equation for the height of fluid in the tank,
b) Create a Simulink model to numerically solve this differential equation and plot the height of the fluid as a function of time for $h(0) = 1$ m.

c) Plot the volume of fluid leaving the tube for h(0) = 0.3 m to h(0) = 1 m

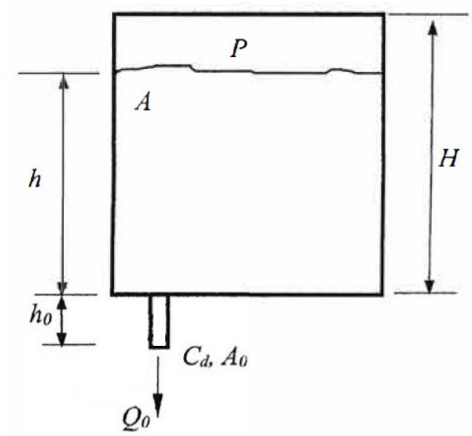

Figure 10. Geometry for differential equation draining homework problem.

Another course using the devices is ME460, Experimental Mechanics which includes an introduction to experimental measurements and their role in the mechanical design process. The course also includes theory and application of static and dynamic instrumentation to include: strain, vibration, temperature, and pressure transducers. Additionally, the course includes a hands-on laboratory experience which constitutes one-half of the course. For the fall 2021 course offering, a three student group has been tasked to fully instrument the second generation HVT2 hydrostatic vacuum device (clear tube variant). The students should fully instrument the device for temperature, pressure, velocity, and flow rate measurement capability (at a minimum). There are two working fluids (air and water), and the devices should use data acquisition methods to collect and record pressure and temperature (at a minimum) data versus time of both working fluids.

Future work

Much of the work described here is in its early form. We plan to modify the "Sidebo Lab," (named in honor of one of the authors of this paper, a Distinguished Visiting Professor at USAFA for several semesters) as we run more students through the courses and plan to iterate on the learning objectives. We survey the students about what they like/wish with the lab, and we also ask them to draft a Part 3 of the lab. From the current lab handout procedures: "Make comments on how this lab could be improved, or expanded to measure additional principles from Chapters 1-6 (reference 5). To do this, draft a "Part 3 section" that could be used in a future lab. You are free to modify the apparatus, or add a second one for part 3 (if you do this include appropriate figures)." This particular lab concept has motivated enough interest that we had multiple students volunteer to do ME499 independent studies to further develop the apparatus.

This study mentioned four courses that use the new hydrostatic vacuum devices. These devices could be used to study other topics from these courses other than the ones listed here. For example, in Fluid Mechanics, the hydrostatic vacuum devices could be used to explain the concept of computational fluid dynamics (CFD). The geometry is simple enough the device could be modeled and demonstrated using commercial software as an additional lab event or project. Other courses in the Mechanical Engineering curriculum could also use the devices than the four listed here. For example, our ME 330 Mechanics of Deformable Bodies course could also do a bending stress analysis on the hardware of the hydrostatic vacuum devices used to hold the main tubes to the hall.

In the future we would like to use quantitative assessment in the form of anonymous surveys so the lab(s) can be evaluated for its effectiveness in improving students' experiences in experimental fluid mechanics analysis and in improving students' ability to use appropriate technical language when discussing the differences between test and analytical results. Ideally our assessment results will indicate that most students developed a much more sophisticated understanding of analysis and testing as a result of these experiences. We will model these surveys after similar work in this area [8] and base our approach on similar mechanical engineering teaching efforts that attempt to shift from subject-based learning to problem-based learning [9].

Conclusions

In the past, our department has purchased expensive "turn-key" laboratory setups to demonstrate thermo-fluid concepts - often costing thousands or tens of thousands of dollars. The goal to supplement the existing thermal fluid science experiments with a new lab event to demonstrate the hydrostatic vacuum concept was accomplished. Two iterations of the hydrostatic vacuum device were built and tested. The current iteration has a small footprint of approximately 30 cm by 30 cm, is relatively low-cost (~$143 in materials as of early 2022), and can be built with basic hand tools. To date, approximately 100 students have used the devices which has been well received anecdotally. Future work will quantify the improvements in student learning and expand the use of the devices for more courses in the mechanical engineering curriculum.

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