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Hands-On Fluid Flow Trainer to Support Experimental Learning

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Hands-On Fluid Flow Trainer to Support Experimental Learning

Abstract

A majority of engineering students will not specialize in fluid mechanics; however, many will take a course on basic fluid flow applications and fundamental theories. The effective use of demonstrations and hands-on learning, can be exceptional tools for solidification of theoretical understanding of fluid flow concepts for students. Several commercially available laboratory trainers for fluid flow focus on a narrow range of applications and are typically at a cost of between $20k to $40k that can preclude the purchasing of multiple trainers and their use as hands-on equipment. This results in the need for a fluid flow trainer that is complex enough to demonstrate a wide range of fundamental fluid mechanics principles for various piping flow arrangements while still making the trainer accessible and relatable to students that are not going to specialize in fluid dynamics.

A unique hands-on fluid flow trainer was designed and fabricated to allow students to more easily visualize and internalize the concepts they will likely need in various follow-on fields of study. The developed trainer features a unique flow path arrangement that allows the selection between multiple piping and valve arrangements to support tank-to-tank filling and draining operations instead of the typical recirculating flow paths seen in many fluid trainers. Additionally, the trainer supports the demonstration of qualitative impacts of major and minor head losses through different piping and valve configurations as well as the implementation of vented manometers to allow students to directly see and correlate fluid head terms with pressure. This trainer is robust enough for use in a lab and/or classroom environment and allows complete operation by students with only brief instructor direction prior to use. This is accomplished by incorporating a tank overflow path that allows students to operate with a lab guide, but without constant instructor oversight. The implementation of this hands-on trainer, through the use of developed lab exercises that support small teams of students, has proven to be extremely effective at solidifying concepts learned in the classroom. This paper outlines the development, design, and implementation of a fluid flow trainer that can be fabricated with off the shelf components for approximately $7k, supporting the fabrication of multiple trainers and allowing for smaller lab group sizes and more hands-on learning to improve fundamental knowledge of fluid flow concepts for students.

Introduction

One of the unique aspects of the United States Naval Academy is the fact that every graduate, regardless of major, is required to earn a bachelor of science degree. As such, all majors are required to take a series of core curriculum courses which support the necessary technical background to earn this degree. Students in the School of Mathematics and Science and the School of Humanities and Social Sciences are all required to take a course titled "Principles of Propulsion" which focuses on basic thermodynamics and fluid flow and in particular how these principles are applied to naval applications. General topics include energy conversion, fluid flow, hydraulics, steam cycles, gas turbine cycles, and internal combustion engine cycles. Additionally, coverage of heat exchangers, refrigeration and air conditioning is included. As this course is required for a very wide range of students with varied backgrounds related to the principles being presented, the effective incorporation of lab exercises within the course curriculum is paramount to the understanding of concepts for students. The fluid flow trainer presented herein was developed to improve the "Principles of Propulsion" course for non-engineering majors at the United States Naval Academy, however the ability of professors and instructors to demonstrate key fluid flow principles with the trainer, in an engaging manner and with a unique flow path arrangement, will benefit engineering majors as well.

The value of hands-on exercises and laboratory experiments in enhancing the academic program for students is clearly documented [1] - [4]. The design and development of interactive exercises is vital to the growth and development of students and supports solidification of concepts presented in the classroom. As will be presented, the developed fluid trainer provides a unique method to involve all students in hands-on operation of components as well as a means for students to provide direction and guidance to other students in the execution of lab exercises. Through the use of this learning method, students are able to better grasp concepts related to major and minor head losses, the applicability of Bernoulli's equation, and pressure measurement techniques. The designed fluid trainer is a significant improvement in the overall learning experience for students at the Naval Academy. It is a robust trainer that will serve thousands of students for years to come in an introductory thermodynamics and fluids course for non-engineers and one that will certainly be adapted for other courses within engineering major curriculums.

Background

Fluids trainers are commonly used to support demonstrations and to some extent hands-on learning in thermodynamic and fluid courses**.** Trainers are developed and available for both introductory and higher-level courses, however trainers do not always include the full hands-on engagement that enables students to gain a better understanding of presented concepts [5] – [8]. This paper focuses on the development and implementation of a replacement hands-on fluids trainer designed for non-engineers in a basic thermodynamics and fluids course.

The previous fluids trainer used for the Naval Academy's "Principles of Propulsion" course was a single trainer that supported demonstrations with a minimal amount of hands-on interaction with students. The trainer consisted of a recirculating flow setup, as seen in Figure 1, that allowed students to observe fluid flow characteristics and conduct basic calculations. Specifically, this trainer supported demonstration of major head losses as well as minor head losses. It also supported an understanding of flow through a venturi and the use of venturis in calculating flowrate based on a provided characteristic curve. The pipe flow setup consisted of a series of pressure taps that were aligned to a manometer to allow for obtaining pressure measurements at various points in different flow paths. Two main lines, of different diameters, allowed for determining the impact of major head losses on pressure.

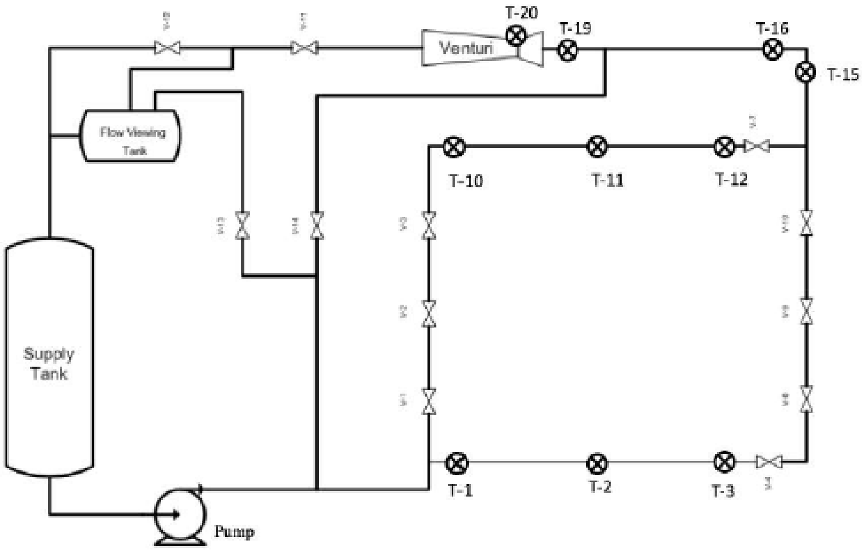


Figure 1. One-Line Diagram of Prior Fluids Trainer

With only one trainer available, this setup only allowed a brief amount of hands-on operations by students. For a typical class size of 20 students only a few students were able to actually manipulate valves and/or directly take measurements during a lab period. Additionally, the overall functionality of the trainer to demonstrate a wide range of fluid flow applications was limited based on only two main flow paths with pressure taps. Finally, challenges associated with filling and venting the system, inadvertent draining of the venturi during valve operations, and improper valve operations resulted in air entrapment that impacted manometer operations and contributed to the desire and need to develop a trainer more suited to the goal of experimental learning for students.

In order to find a suitable replacement trainer, commercially available trainers were initially investigated. Six trainers were evaluated with the majority of the trainers costing between $20K and just under $40K, with an additional associated cost for separate hydraulic benches for most of the trainers [9] – [14]. Specific trainers evaluated included TecQuipment Fluid Friction Apparatus H408 [9], TecQuipment Losses in Piping Apparatus H16 [10], Armfield C6-MkII-10 Fluid Friction Measurements [11], Armfield F1-22 Energy Losses in Bends and Fittings [12], Gunt HM 120 Losses in Pipe Elements [13], and the Gunt HM 112 Fluid Mechanics Trainer [14]. These trainers are all professionally built and they all contain some of the desired aspects of a trainer for fluid flow principles, however many of the trainers were too complex for non-engineering students and likely would not support a full hands-on experience for students. The decision was made to develop a trainer that captured a broader range of fluid flow principles, would support significantly more hands-on operations, and that would be able to be produced at a lower cost to allow the procurement of multiple trainers.

Design and Development

As an entering argument to the development of a new fluids trainer, a set of both trainer and teaching goals was developed. These goals were developed based on analysis of the current system and feedback obtained during prior labs. Trainer goals included the following:

1. Clear visualization of flow paths for students
2. Significant opportunities for hands-on operation by students
3. Cost that supported the design and building of multiple trainers
4. Open system that supported tank-to-tank pumping and draining operations
5. Use of manometers to allow students to visualize pressure changes
6. Incorporation of multiple valves common to fluid systems

The clear visualization of flow paths would allow students to focus on understanding principles instead of struggling to understand the trainer setup. In order to support significant hands-on operation by students it was also necessary to make the trainer robust enough to support use by approximately 400 students each academic semester. This would support a normal teaching load for the Naval Academy's basic thermodynamics and fluids course for non-engineers. Closely combined with the goal of significant hands-on operation was the need for multiple trainers. In order to have all students integrally involved in the learning process, assuming a typical class size of approximately 20 students, it was necessary to develop multiple trainers. In order to maximize availability of trainers for different course sections and potentially other courses, these trainers also needed to be mobile in order to support movement between various locations. Many of the fluid flow problems presented in the thermodynamics and fluids course for non-engineers are tank-to-tank problems that have direct applications to naval applications and are also relevant to many every day and commercial applications. The use of a tank-to-tank setup allows a range of options for flow demonstrations and includes the ability to demonstrate draining processes. Manometer basics are introduced in nearly all fluids courses and the need to have an easy and clear vented manometer in place was vital to this particular lab. Lastly, the incorporation of different valve types into the system was desired based on students being introduced to a number of different types of valves in the course, but never having seen them in operation. These trainer goals provided the framework for the physical design of the trainer. In addition to trainer goals, specific teaching goals were generated and included the following:

1. Observe and/or determine major and minor head losses
2. Perform flowrate calculations
3. Apply Bernoulli's equation
4. Incorporate valve safety discussions into use of trainer

A fundamental understanding of the impacts of major and minor head losses on fluid flow was desired to be incorporated into the trainer with improvements on the demonstration abilities in prior trainers. A basic understanding of flowrate measurements and the continuity equation was also desired. The incorporation of the Bernoulli equation into the trainer and an expectation for students to be able to conduct basic calculations using data gathered from the trainer would allow solidification of concepts learned in class. The use of multiple valve types and the ability to isolate piping sections would provide the ability to discuss valve safety expectations.

In order to support the overall goals, parts were procured that supported flow path visualization. Specifically, the trainer was designed to be mounted on a semi-clear plexiglass pegboard, with semi-clear drain tanks, and high-pressure PVC plastic tubing for manometers and flow between valves. This setup would support student observation of fluid flow. The incorporation of four different valve types in the system (swing check, ball, gate, and globe) allowed for the observation of different impacts on flow while also facilitating discussion points on why these valves were used in specific system locations. The decision to make the trainer mobile presented initial challenges, but during the building stage modifications were made to support the installation of brackets that assisted with trainer stability following the mounting and filling of tanks. The final one-line diagram of the trainer is presented in Figure 2.

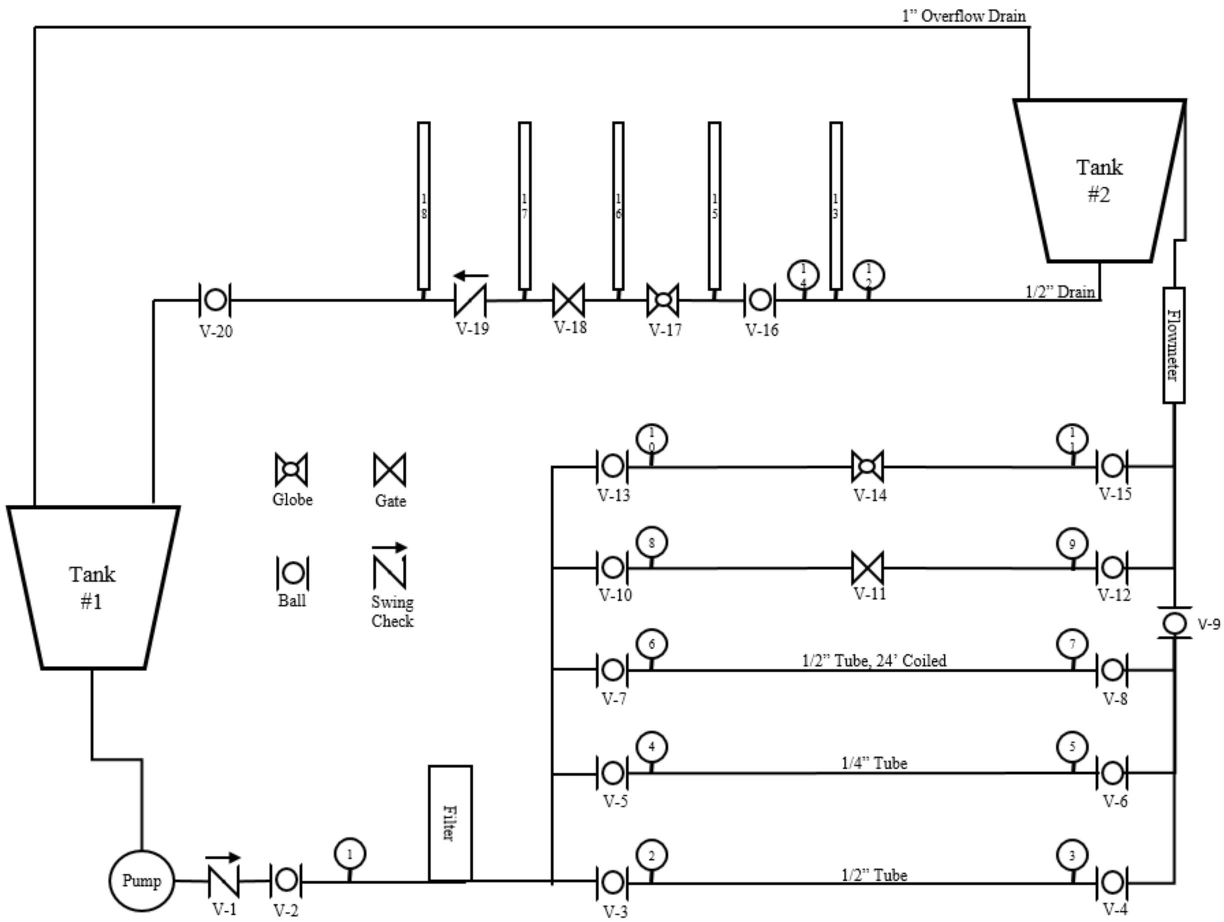


Figure 2. One Line Diagram of Final Fluid Trainer

Unique features of the final trainer include an overflow drain from Tank #2 to Tank #1 that allows the included pump to run without concern while students are working through the lab. Additionally, the positioning of five manometers between four different types of valves on a ½ inch diameter drain path between Tank #2 to Tank #1 supports evaluation of minor losses and an understanding of pressure measurements using manometers. Students are able to touch, operate, and investigate spare valves that are provided with the trainer to aid in visual understanding of flow paths through the valves (Figure 3).

Figure 3. Valves for Student Observation and Operation

Testing and Modifications

After fabrication of the first trainer, a pilot program was run with 15 groups of three to five students to assess the executability of a designed lab and the overall learning experience of the students. Feedback was solicited for improvements from both students and instructors. Feedback was overall very positive with most comments focused on the hands-on benefits of the entire trainer and the ability to highlight multiple fluid flow concepts. Prior to execution of the lab it was expected that all students had been introduced to basic fluid flow theory. Specifically, students were expected to be familiar with manometer operations and the general concept of how to read manometers and use them for pressure calculations. Students were also expected to be familiar with calculation processes for major and minor head losses as well as the use of the Bernoulli and/or pump head equation. Students were also expected to be introduced to common valve types and their advantages and disadvantages. The trainer used in the pilot program is seen in Figure 4.

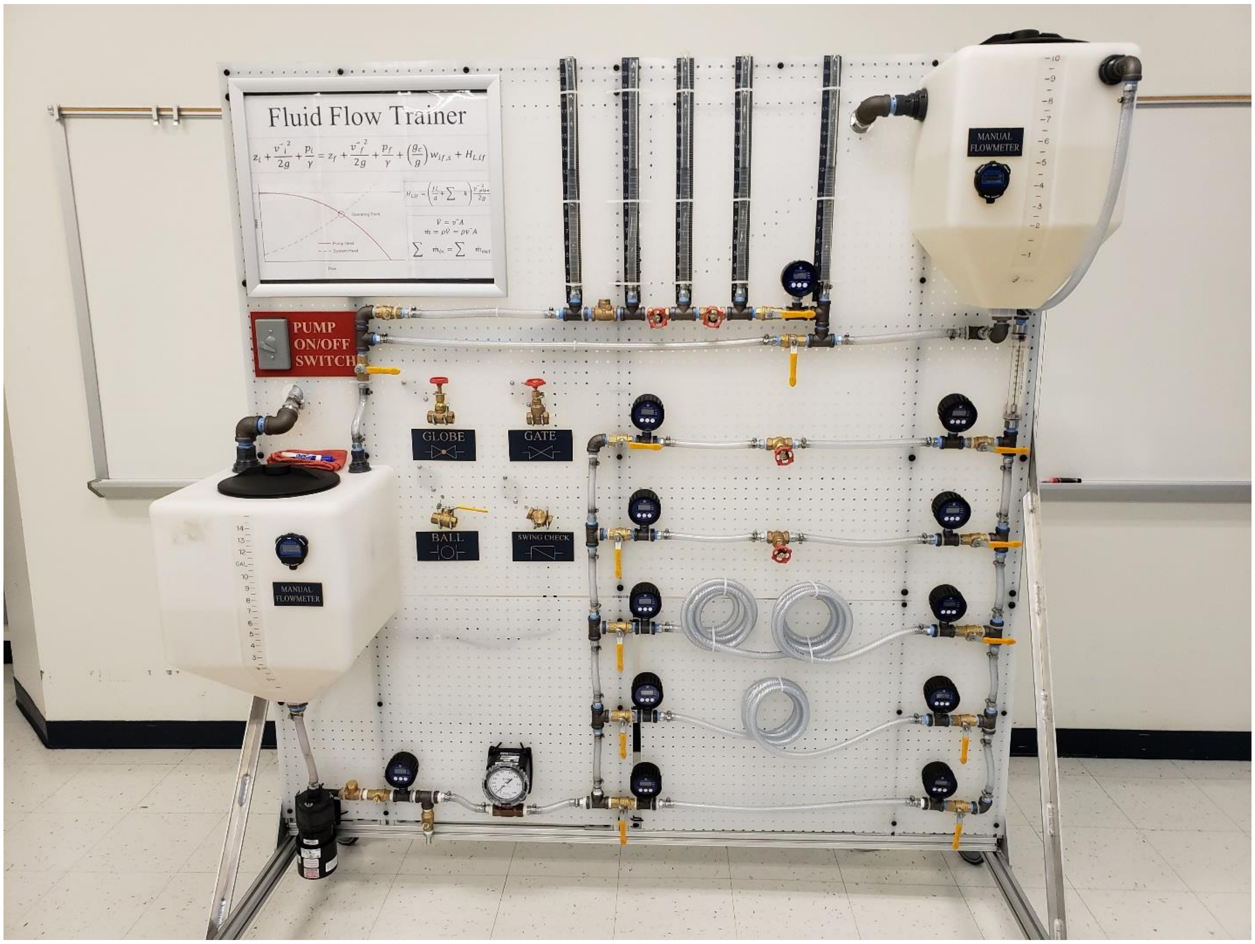
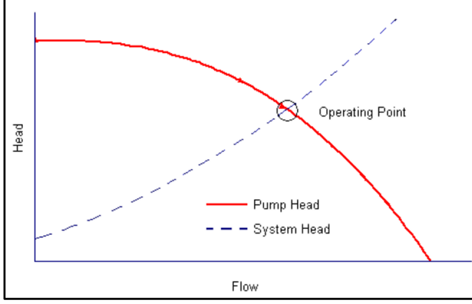


Figure 4. Fluid Flow Trainer used in Pilot Program.

A preliminary lab guide was developed that supported groups of four to five students using the trainer as a team with limited specific guidance from instructors. To support maximum hands-on opportunities for the students, a brief lab description was provided to each group with students then expected to execute the majority of the lab during the provided lab time. Common fluid flow equations to include Bernoulli's equation and head loss equations were provided on the trainer to allow for quick reference during the lab (Figure 5), however longer required calculations were clearly marked in the lab guide and expected to be finished at a later time.

$$z_i + \frac{\vec{v}_i^{\,2}}{2g} + \frac{p_i}{\gamma} = z_f + \frac{\vec{v}_f^{\,2}}{2g} + \frac{p_f}{\gamma} + \left(\frac{g_c}{g}\right) w_{if,s} + H_{L,if}$$



$$H_{L,if} = \left(\frac{fl}{d} + \sum k\right)\frac{\vec{v}_{pipe}^{\,2}}{2g}$$

$$\dot{V} = \vec{v}A$$
$$\dot{m} = \rho\dot{V} = \rho\vec{v}A$$
$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

Figure 5. Fluid Trainer Quick Reference Equations

During the course of the experimental and testing phase with students, several observations were made that resulted in improvements to the trainer. Specifically, the fittings between components were upgraded from steel to stainless steel to minimize corrosion issues. This helped minimize the generation of wear particles that caused discoloration of the water in the trainer after a few weeks of operation during the testing phase. Additionally, a clear filter was incorporated into the trainer to maintain overall system cleanliness and improve trainer longevity. The manometer setup was shifted to rigid clear plastic tubes to allow for ease of reading for students. One piping line was shifted to a smaller diameter tubing vice a different tubing length to promote more questioning and analysis by the students and a cover was placed over one of the piping configurations so students were unaware of piping size difference and had to question the reason for the differences in pressure readings. Finally, pressure gauges were shifted from digital pressure gauges to oil-filled vibration resistant analog gauges to be more consistent with many of the current gauges used in the Navy and to minimize student confusion over slight fluctuations in the digital pressure gauge readings.

After completing modifications based on feedback and testing, parts for three additional trainers were procured and manufactured, at a cost of approximately $7K, to support lab use during the spring semester of the 2022-2023 academic year. An image of the final trainer is provided in Figure 6.

Figure 6. Final Trainer Design

Lab Use

The primary goal of the designed lab procedure was to create an interactive, educational, enjoyable, and student driven process to visualize fluid flow concepts and to relate them to in-class learning. To support this student driven process, the students were divided into a supervisor role, a team lead role, and multiple valve/component operators (Figure 7). This process is consistent with typical operations used on naval vessels and supports students gaining an understanding of supervisory roles as well as operator roles. The lab is subdivided into four specific parts which allows students to rotate between positions.

Figure 7. Students Engaged in Fluids Trainer Use

The first part of the lab guide focuses on flow rate calculations and provides an opportunity for students to understand system alignment. Students are challenged to line up a proper flow path between Tank #1 and Tank #2 through the lowest flow path as seen in Figure 8. Students are able to measure flowrate via a simple measurement of tank levels and using provided stop watches and are then able to compare with a flowmeter mounted in the system. Using data collected during the lab and information on pipe diameter they are then able to use basic calculations to determine fluid flow velocity.


Figure 8. Fluid Trainer Lowest Flow Path

The second part of the lab introduces students to pressure losses in the system due to filters, piping major head losses, and minor head losses due to bends and valves. Differential pressure across the installed filter is measured and students are prompted to explain the impact of debris buildup on pressure readings. Students are then able to initiate flow through five different piping branches. The five branches include straight ½ inch diameter tubing, straight ¼ inch diameter tubing, ½ inch diameter tubing with loops to increase length, ½ inch diameter tubing with an installed gate valve, and ½ inch diameter tubing with an installed globe valve (Figure 9).

Students are challenged to determine the reason for differences in pressure losses based on measurement of pressures while pumping water from Tank #1 to Tank #2 through one line at a time.   They are also able to observe the impacts of using a globe valve for throttling purposes.

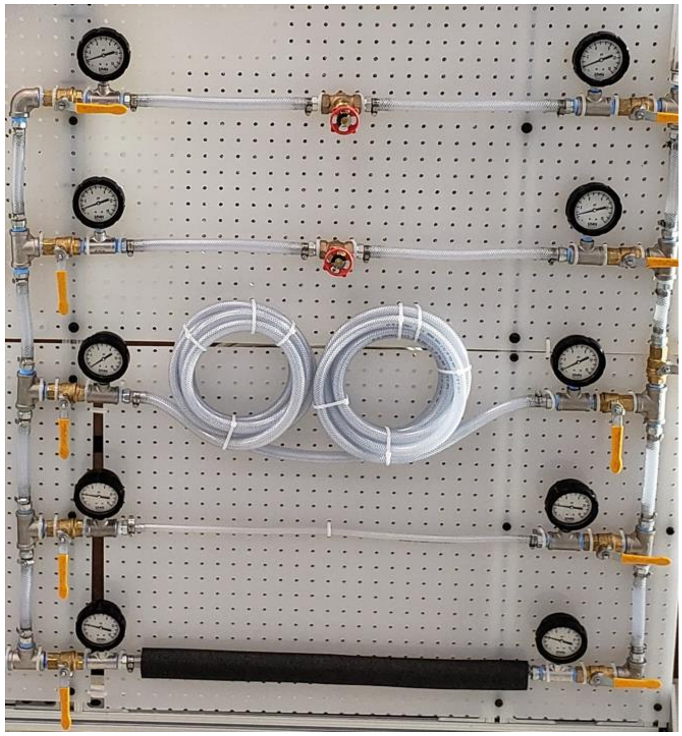


Figure 9. Five Flow Paths for Pressure Evaluations

The third section requires students to investigate gravity draining from Tank #2 to Tank #1 through a piping branch with installed valves to include a ball valve, globe valve, gate valve, and swing check valve. Rigid manometers between each valve allow students to observe pressure changes across the different types of valves and determine approximate k-values for each type of valve. Students are also able to perform static pressure calculations based on the height of water in a manometer and compare this to an installed pressure gage. Figure 10 shows the manometer setup.

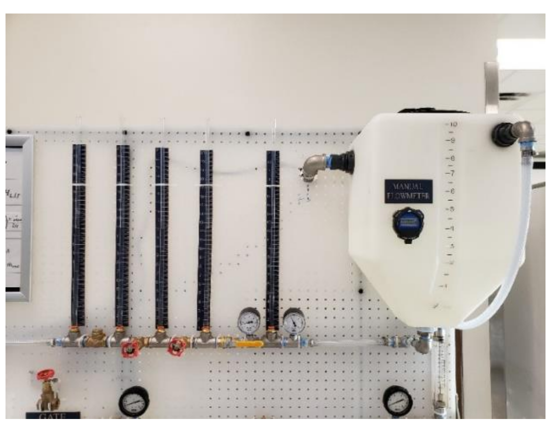


Figure 10. Manometer Arrangement for Tank Draining

The final portion of the lab requires students to obtain measurements of terms used in the Bernoulli equation, to include height and pressure at various state points when pumping from Tank #1 to Tank #2. These state points and flow path can be seen in Figure 11. By collecting this data, students are then able to perform calculations using the Bernoulli equation to determine pump specific work and head loss while making some simplifying assumptions. This process results in a better student understanding of the tie between all terms in the Bernoulli equation and their impact on an actual pumping operation.

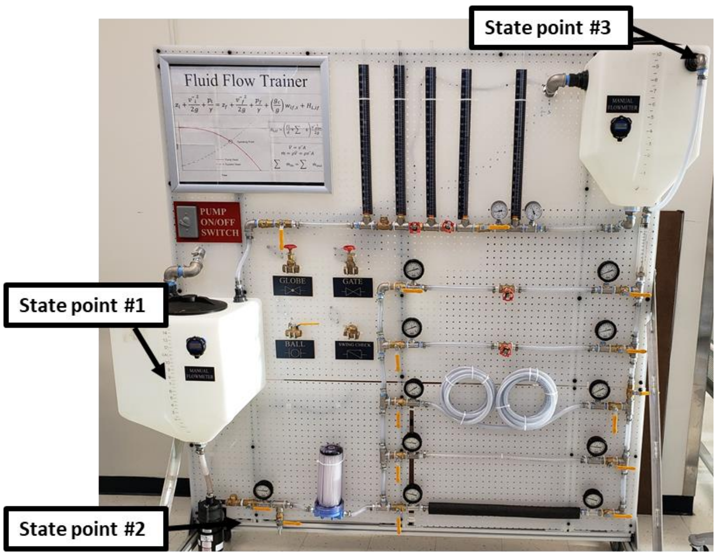


Figure 11. State Point Arrangement on Fluids Trainer

The use of a lab guide that requires all students to be fully engaged with the performance of tasks is extremely beneficial. Each student is able to serve in various roles (supervisor, team lead, valve operator) during a different segment of the lab which allows them to grasp fluid flow concepts through hands-on learning with a guide that is structured enough to require minimal instructor oversight to prevent any risk to the trainer and allows the students to self-learn.

Conclusions

The designed fluids trainer presented in this paper provides a unique, student driven, hands-on experience that promotes intellectual curiosity, promotes student engagement, and solidifies basic fluid flow concepts. While the development of an “in-house” trainer is not necessarily unique, the ability for students to experience and visualize a wide range of fluid flow concepts to include minor and major head losses, differential pressure readings, manometer use, flowrate calculations, and Bernoulli equation calculations based on recorded data, in a completely hands on manner, is an exceptional improvement in experimental learning. The development of a student driven lab that allows students to operate a pump, learn to read gauges and flowmeters, manipulate valves in order to properly align flow paths, and perform calculations that demonstrate the fluid flow concepts introduced in class has been well received by students and all instructors and professors who have had the opportunity to use the developed trainer. The designed trainer is already having a positive impact on student learning at the United States Naval Academy.

By designing a trainer at a cost of approximately $7K, four total trainers were able to be built which allows small teams of four to five students in each class to be fully involved in a dedicated fluid flow lab exercise. The developed trainer was used to provide approximately 350 non-engineering students a hands-on fluids experience in the spring of academic year 2022-2023 and will continue to be used for between 350 and 400 students each semester for the foreseeable future. While this trainer was designed for a non-engineer thermodynamics and fluids course, the trainer is easily adaptable to other courses within an engineering curriculum. The ability to clearly demonstrate an extremely wide variety of common fluid concepts can support students across all engineering curriculums.

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